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Space Power Facility Reverberation Chamber Calibration Report

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1.0 Introduction

1.1 Background

The Space Power Facility (SPF) vacuum chamber at the NASA Glenn Research Center (GRC) Plum Brook Station (PBS) near Sandusky, Ohio, is being prepared for use as an electromagnetic compatibility (EMC) test facility. Tests and analyses of the SET Chamber have shown that the facility can be configured for reverberant chamber operation with a conductive paddle structure, called a tuner, for radiated susceptibility testing of equipment-under-test (EUT's).

1.2 Purpose

This document describes the process and results of calibrating the Space Environmental Test (SET) Electromagnetic Interference (EMI) Test facility (Figure 1) at PBS SPF according to the specifications of IEC61000-4-21 for susceptibility testing as required by the Electromagnetic Environmental Effects (E3) "Reverberant Chamber System Requirements Document," GRC-SET-REQ-033 from 100 MHz to 40 GHz. The procedures outlined in GRC-SET-PLAN-041, "Space Environmental Test (SET) Reverberation Chamber Calibration Test Plan," were followed.

1.3 Summary

The chamber passed the field uniformity test, in both the empty and loaded conditions. However, it is anticipated that a crew vehicle of a similar size to the Orion Crew Exploration Vehicle (CEV) will require recalibration with more loading than was achieved with this test. In addition, the biggest challenge may be providing the power to generate a 200 V/m electric-field (E-Field).

1.4 Prerequisite Testing

The calibration testing was preceded by a shielding effectiveness test, a radio frequency (RF) emissions test, and a tuner performance test.

The shielding effective test was performed before this calibration test to ensure the SPF chamber and chamber treatments provide the levels of shielding required by GRC-SET-REQ-033. The test was performed according to GRC-SET-PLN-042, "Electromagnetic Shielding Effectiveness of the Space Power Facility Test Plan."

After the shielding effectiveness test, an emissions test was performed to ensure that the levels radiated from the chamber are in compliance with limits specified by the National Telecommunications and Information Administration. This test was performed according to GRC-SET-PLN-043, "Radio Frequency Emissions of the Space Power Facility Test Plan."

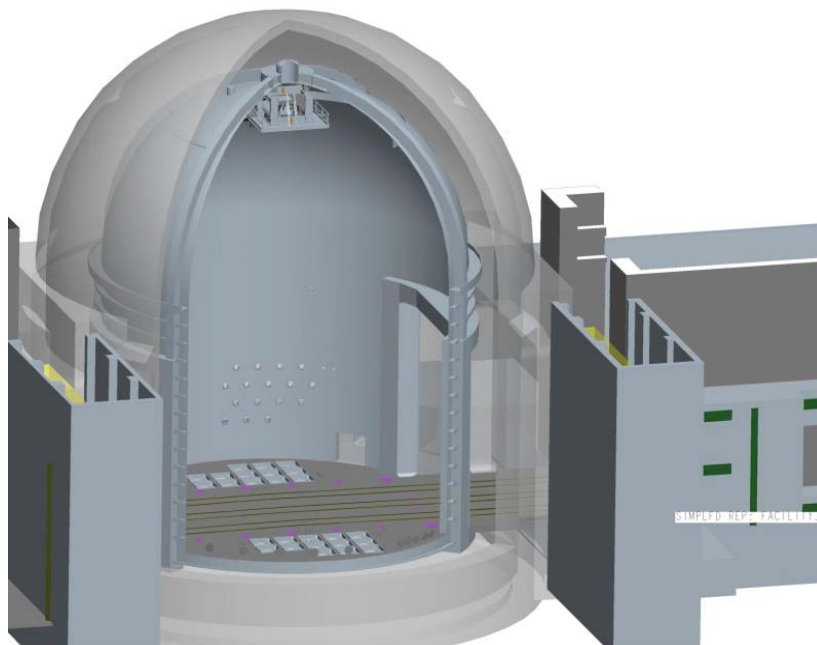


Figure 1.—SET EMI Test Facility Chamber

Following the shielding effectiveness test, a tuner performance test was conducted. The tuner performance test confirmed the design and placement of the tuner and transmitting antennas in the SPF chamber were suitable for reverberant testing. This test was performed according to GRC-SET-PLN-044, “Tuner Performance Test Plan.”

2.0 Applicable Documents

2.1 General

This section lists documents cited in other sections of this plan.

2.2 Applicable Government Documents

The specifications, standards, and handbooks in Table 1 form a part of this document to the extent specified herein.

TABLE 1.—APPLICABLE GOVERNMENT DOCUMENTS

Document Title	Document Number	Revision
EMI Chamber Penetration Shields Installation and Removal	PBSPF-091	Baseline
Reverberant Chamber System Requirements Document	GRC-SET-REQ-033	
Space Environmental Test (SET) Reverberation Chamber Calibration Test Plan	GRC-SET-PLN-041	Baseline
Electromagnetic Shielding Effectiveness of the Space Power Facility Test Plan	GRC-SET-PLN-042	Baseline
Radio Frequency Emissions of the Space Power Facility Test Plan	GRC-SET-PLN-043	Baseline
Tuner Performance Test Plan	GRC-SET-PLN-044	
E3 hazard analysis report	GRC-SET-RPT-045	Baseline
Glenn Safety Manual	GLM-QS-1800.1	
Glenn Occupational Health Programs Manual	GLM-QS-1700.1	

2.3 Nongovernment Publications

The publications in Table 2 form a part of this document to the extent specified herein.

TABLE 2.—NON-GOVERNMENT APPLICABLE DOCUMENTS

Document Title	Document Number	Revision
Electromagnetic compatibility (EMC) –Part 4-21: Testing and measurement techniques –Reverberation chamber test methods	IEC 61000-4-21	2003-08
Time-Domain Propagation Measurements of the NASA Space-Power Facility	NTIA Technical Report TR-10-471	Oct-2010
An Electromagnetic Evaluation of the NASA Space Power Facility at Plum Brook Station	NIST Tech Note TN-1558	July 2011
Environment Conditions and Test Procedures for Airborne Equipment	RTCA/DO-160	Revision F December 2007

2.4 Order of Precedence

In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3.0 Test Setup

3.1 Tolerances

A single E-Field probe is used for data gathering, to reduce/eliminate the errors introduced by different probe calibration factors. The spatial tolerance for positioning the E-Field probe throughout this procedure was 30 cm (1 ft). All E-Field probe positions were recorded to establish the actual boundaries of the working volume. The tuner and transmitting antenna positions were fixed with mounting hardware or permanently marked in the SPF chamber for repeatability throughout the calibration and subsequent EUT tests. The transmitting antenna orientations were also fixed with mounting hardware or permanently marked on their mounting fixtures. The tuner is removed for vacuum operations and re-installation will be within 1 in. of original location.

3.2 SET Reverberation Chamber Setup

Prior to doing any EMI testing PBSPF-091 EMI Chamber Penetration Shields Installation and Removal check-sheet needs to be performed. This check-sheet is very thorough and covers installation of the EMI Door 5 assembly, polar crane preparations, fabric covers installation, hatch flange, etc. It is uncertain the effect the orientation of the polar crane platform has on the E-Fields. For our testing the crane was clocked as shown in Figure 2.

A single tuner was placed in the chamber, but outside of the working volume as shown in Figure B.2 to Figure B.7. The working volume defined by this report is the vertical height between 1 m above the floor and 23 m (76 ft) above the chamber floor, and a horizontal area roughly 15 m (49 ft.) by 22 m (72 ft). The Z-fold tuner was mounted on a support structure designed for the SET chamber.



Figure 2.—Polar Crane Orientation Relative to East Door

The position and orientation of each transmitting antenna was meant to maximize stirring early in the E-Field propagation path and avoid direct illumination of the working volume. The position and direction of the transmitting antennas was based on the beam width of the antenna and the requirement to avoid direct illumination of the working volume. Transmitting antennas for frequencies above 300 MHz were mounted on a custom fixture near the Personnel Access door (sometimes referred to as “Door 5”) and interface panel to minimize cable losses, but also oriented to prevent direct illumination of the working volume. The biconical antenna, used for frequencies between 100 MHz (50 MHz) and 300 MHz, was mounted on a tripod 1 to 2 m above the chamber floor near the tuner, but not closer than 1 m to the tuner. Due to the dipole radiation pattern, the biconical transmitting antenna axis was oriented horizontally with one end pointing toward the center of the chamber. The position and polarity of each transmitting antenna and tuner was marked and recorded to duplicate the tuner and transmitting antenna positions per IEC61000-4-21. The mode stirring tuner is shown in Figure 3.

The receiving antennas measured the power in the chamber at various arbitrary positions in the chamber after each tuner cycle. However, the orientation of the receiving antennas did not align with the transmitting antennas (they were cross-polarized to each other). Furthermore, for frequencies between 300 MHz and 40 GHz, the receiving antenna was pointed away from the transmitting antenna to avoid direct illumination. For 100 to 300 MHz, the axis of the receiving biconical antenna was parallel to the axis of the receiving antenna to avoid direct illumination due to the omnidirectional radiation patterns of these antennas. The receiving antenna was mounted on a tripod 1 to 2 m above the chamber floor.



Figure 3.—Mode Stirring Tuner, Inside the Chamber

As mentioned earlier, the E-Field was measured with a single triaxial E-Field probe. The data taken in the x, y, and z axes are shown in Section 5.0. The probe was relocated to measure the E-Field in several pre-determined locations, and was moved to a new location after each tuner cycle. Probe positions near the tuner determined the sufficiency of stirring near the tuner and extended the working volume. The locations of the remaining probe positions were selected to define as large a rectangular floor volume as possible, as shown in Figure B.1.

The three elevations of the probe were achieved using three different methods. The 1 m elevation was achieved by mounting the probe on a 2-in.-diam., 1 m custom Delrin (DuPont) tube mounted to an aluminum baseplate. To elevate the probe to 11 m the custom 1 m Delrin tube was attached to multiple 2-in.-diam. carbon fiber segments and raised using a Will-Burt commercial mast system. For the 18 m elevations an 8-ft-diam. helium filled weather balloon was used. The E-Field probe was suspended 4 ft below this using a Delrin cross and parachute cord. A laser system was used to accurately position the probe, and four guy lines helped stabilize the movement of the balloon. The stillness of the air within the chamber kept the movement of the balloon to a minimum, and met the tolerance requirements of this test.

3.2.1 Unloaded Chamber Calibration Probe Locations

For the unloaded chamber calibration there were multiple variations of the number of probe locations (based on frequency ranges). For the 100 to 300 MHz band E-Field data was taken for 18 different probe positions but taken in two different sets. Seven of the 18 probe positions (see Figure B.3) were taken at 20 paddle rotations to save time. The other 11 probe positions (Figure B.2) were sampled at 50 paddle rotations. Since the data set from the 11 probe positions met the IEC61000-4-21 field uniformity requirements the other 7 probe position's data was not used. For the frequency band of 300 MHz to 1 GHz, 18 E-Field probe locations were measured. Above 1 GHz where uniformity improves with decreasing wavelength all the frequency bands used the same ten probe locations (Figure B.8, minus center location).

3.2.2 Loaded Chamber Calibration Probe Locations

For the loaded calibration, one standard set of 11 probe positions for all the frequencies were used (Figure B.8).

The elevation of the probe was achieved with a tripod at 1 m. To elevate the probe to 11 and 18 m, a helium filled balloon was used. The stillness of the air within the chamber kept the movement of the balloon to a minimum, and met the tolerance requirements of this test as verified by a laser positioning system.

Between 100 MHz and 1 GHz, 18 E-Field probe locations were measured due to the unique shape of the SPF chamber. Because the IEC61000-4-21 field uniformity requirements were met below 1 GHz, only 10 E-Field probe locations were required above 1 GHz where uniformity improves with decreasing wavelength. The 10 probe locations that were used from 1 to 40 GHz are shown in Figure B.8, minus the center location.

The E-Field probe was mounted on a bracket which elevated it 35.5° above the horizontal plane which pointed the x-axis vertically upward. At each position on the circumference of the working volume, the probe axis was pointed toward the wall. For the center position, the probe axis was oriented toward the tuner.

3.3 RF Equipment Setup

The Main Computer controlled the RF equipment and tuner with the Rhode & Schwarz EMC32 application (Figure 4). The version of EMC32 used to capture and process some of the data was 8.5 and version 8.53 was used to further process the data. The test was divided into frequency bands based on the bandwidth of the RF equipment. The frequency list, tuner steps, and RF setup for each frequency band are provided in Section 5.1. The RF equipment is listed in Table 3 and the configurations are provided in Figure B.9 to Figure B.16.

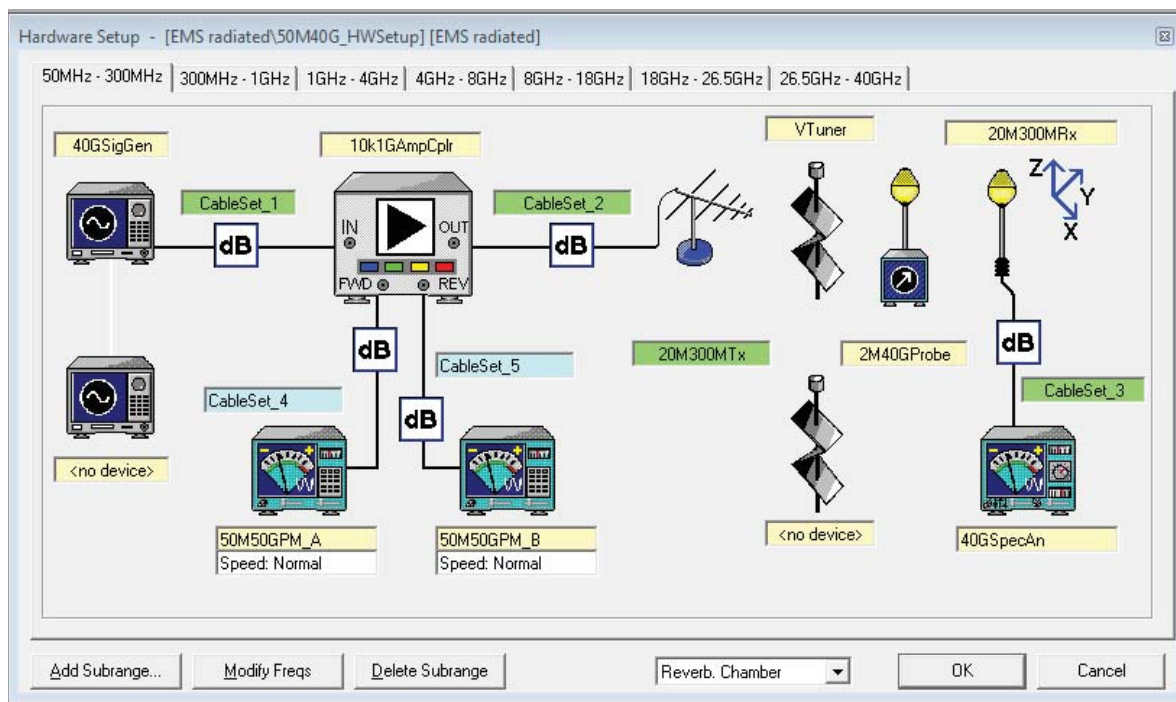


Figure 4.—EMC32 Hardware Setup Screenshot

TABLE 3.—EQUIPMENT USED FOR PBS CHAMBER CALIBRATION

50 to 300 MHz	300 to 1000 MHz	1 to 4 GHz	4 to 6 GHz	6 to 18 GHz	18 to 26 GHz	26 to 40 GHz	Qty.	Item	Mfr.	Model number	Calibration due date
X	X	X	X	X	X	X	1	Signal Generator	HP/Agilent	E8257D	12/16/12
X	X	X	X	X	X	X	1	Spectrum Analyzer	Rohde & Schwarz	FSV40	9/14/11
X	X	X	X	X	X	X	1	Power Meter	Agilent	N1914A	3/8/12
X	X	X	X	X	X	X	2	Power Sensors	Agilent	N8487A	10/1/11
X	X	X	X				2	PM 2.4-N Adapters	Pasternack	PE9503	
				X			2	PM 2.4-SMA Adapters	Pasternack	PE9654	
					X	X	2	PM 2.4-2.9 Adapters	Fairview Microwave	SM3185	
X	X	X	X	X			1	DC Block	Pasternack	PE8123	
					X	X	1	DC Block	Fairview Microwave	SD3779	
X	X	X	X	X			1	20 dB Attenuator	Pasternack	PE7017-20	
					X	X	1	20 dB Attenuator	Pasternack	PE7046-20	
X	X	X	X	X			1	SG Adapter	Fairview Microwave	SM3085	
X	X	X	X	X			2	N-FDTHRU Adapter	Pasternack	PE9128	
					X	X	1	SG Adapter	Pasternack	PE9456	
X	X						1	Power Amplifier 1	AR Products	50WD1000M2	
		X					1	Power Amplifier 2	AR Products	30S1G4M3	
			X				1	Power Amplifier 3	AR Products	15S4G8AM2	
				X			1	Power Amplifier 4	AR Products	10S6G18AM4	
					X		1	Power Amplifier 5	IFI	T2618-40	
						X	1	Power Amplifier 6	CPI	VZA6902J1	
					X	X	1	50 Ω Load	Fairview Microwave	ST4015	

TABLE 3.—EQUIPMENT USED FOR PBS CHAMBER CALIBRATION

50 to 300 MHz	300 to 1000 MHz	1 to 4 GHz	4 to 6 GHz	6 to 18 GHz	18 to 26 GHz	26 to 40 GHz	Qty.	Item	Mfr.	Model number	Calibration due date
					X	X	1	50 Ω Load	Fairview Microwave	ST350PL	
					X	X	1	RF Switch	TBD	TBD	
					X		1	Coax/Wvgd Adapter	Fairview Microwave	42AC216	
						X	2	Coax/Wvgd Adapter	Fairview Microwave	28AC206	
		X					1	Directional Coupler 3	AR Products	DC7144A	
			X				1	Directional Coupler 4	AR Products	DC7350A	
				X			1	Directional Coupler 5	AR Products	DC7435A	
					X		1	Directional Coupler 6	AR Products	DC7530	
						X	1	Directional Coupler 7	AR Products	DC7620	
X							2	Bicon. Ant's	A & H System	SAS 543FL	
	X						2	Log Periodic	A & H System	SAS 510-2	
		X	X	X			2	Horn Ant's	A & H System	SAS-571	
					X	X	2	Horn Ant's	A & H System	SAS-574	
X	X	X	X	X			1	Cables	Gore	0SQ01Q0107 8.7-T/V	
X	X	X	X	X			2	Cables	Gore	0SQ01Q0111 18.0-T/V	
X	X	X	X	X			1	Cable	L-Com	CA-6NMNM025	
X	X	X	X	X			1	Cable	AH Systems	SAC-18G-3	
					X	X	1	Cables	Gore	0K0CQ0CQ0 39.4-T/V	
					X	X	2	Cables	Gore	0K0CQ0CQ1 18.0-T/V	
					X	X	1	18 to 40 GHz RX Antenna Cables	AH Systems	SAC-40G-6	
X	X	X	X	X	X	X	2	Antenna Tripods	AH Systems	ATU-510	
X	X	X	X	X	X	X	1	Electric-field Monitor	Amplifier Research	FM7004	
X	X	X	X	X	X	X	1	Laser Interface	Amplifier Research	FI7000	
X	X	X	X	X	X	X	2	100 Ft Fiber Optic Cable Pair	Amplifier Research	FC 7010	
X	X	X	X	X	X	X	1	Electric-field Probe	Amplifier Research	FL7040	
X	X	X	X	X	X	X	1	Tuner Motor Controller	Carousel	AT11	
X	X	X	X	X	X	X	1	Tuner Turntable	Carousel	TBD	
X	X	X	X	X	X	X	1	Main Computer with EMC32	GRC	Version 8.50	
X	X	X	X	X	X	X	1	Tuner Stand	GRC	TBD	
X	X	X	X	X	X	X	1	Tuner	GRC	TBD	
X	X	X	X	X	X	X	1	Ethernet Switch	GRC	TBD	
X	X	X	X	X	X	X	1	Video Computer	GRC	TBD	
X	X	X	X	X	X	X	1	ETS Lindgren Video Camera	ETS Lindgren	VC-04	
								Safety Circuit Assembly	GRC	TBD	

4.0 Calibration Procedure

The reverberation test technique relies on the production of a statistically uniform field within one rotation of the stirring paddle(s). The physical features of the SPF vacuum chamber presented some unique challenges and many unknowns. To determine the viability of performing reverberation testing in the SET vacuum chamber, NASA collaborated with the National Institute of Standards and Technology (NIST) to test the chamber in an empty state and quantify its electromagnetic characteristics. While the NIST study did not intend to perform the chamber calibration, it established the chamber as a good reverberation environment. The end results of the NIST investigation can be read in “An Electromagnetic Evaluation of the NASA Space Power Facility at Plum Brook Station,” by Galen Koepke, John Ladbury, Dennis Camell, Jason Coder, Chriss Grosvenor, Randall Direen, and Jeff Guerriere.

4.1 Time Estimate

The calibration of a reverberation chamber is a rigorous test. Based on recorded test time at the GRC Smart80 Facility, the calibration time per frequency band was estimated as shown in Table 4. This estimate assumes approximately 7 sec per frequency for power leveling and measurement stabilization, 20 sec per tuner step, 15 min per probe position change, and 30 min for RF equipment setup.

Each of the above tests must be repeated for the loaded calibration, which brings the total calibration time estimate to ~229 to 0 percent +20 percent hr. This estimate was used for planning purposes, and was very close to the actual time taken for the test. Refer to Section 5.1 for the Test Summary, which documents the test activities.

4.2 Roles and Responsibilities

The SET E3 calibration personnel were led by a Test Lead and a Test Operator. The Test Lead was the primary lead for safety related processes to ensure that the test was conducted in a safe manner in accordance with Section 4.3 of this document.

The Test Operator was the primary lead for setting up the E3 equipment, running the test and collecting the required data.

4.3 Safety

This test met the requirements of GLM-QS-1700.1, “Glenn Safety Manual,” and GLM-QS-1800.1, “Glenn Occupational Health Programs Manual,” which apply to all work done at Lewis Field and PBS. To manage the RF energy for personnel safety, a hard-wired safety circuit disabled the RF amplifiers and stopped the tuner motion: if an individual depressed the E-stop button in the chamber, if an individual depressed the E-stop button outside of the test chamber, if the Personnel Door was opened, or if the RF energy outside the chamber exceeded the limits specified in the E3 hazard analysis report, GRC-SET-RPT-045.

TABLE 4.—TIME ESTIMATE FOR CHAMBER CALIBRATION

Frequency band (MHz)	Tuner steps	Probe positions	Time to complete (hr)
100 to 300	50	18	41.1
300 to 1000	18	18	18.4
1000 to 4000	12	18	14.6
4000 to 8000	12	10	7
8000 to 18000	12	10	7
18000 to 26500	12	10	6.5
26500 to 40000	12	10	6.5

At the start of each test period, the Test Lead executed the Safety Checklist located in GRC-SET-PLN-041, Appendix G, to ensure the chamber was safe for entry and the system was safe for testing. At the conclusion of each test period the Test Lead executed the safety checklist located in Appendix H to safely configure the chamber for shutdown. The safety circuit inhibits were tested every 30 days with the safety circuit inspection procedure located in GRC-SET-PLN-041, Appendix I.

4.4 Unloaded Calibration

The calibration was largely automated through the use of Rhode & Schwarz EMC32 software on a computer. Before testing began, calibration data for all equipment was collected and programmed into the EMC32 data files. The Test Operator set up the equipment according to the configurations in Figure B.9 through Figure B.16 and the procedures in GRC-SET-PLN-041, Appendix D. The Test Lead then executed the safety checklist for chamber entry, and executed the calibration using EMC32 software as described in the following paragraphs.

The Test Operator initiated EMC32 software which moved the tuner into position 1 and began sweeping the signal generator with a continuous wave from the start of the frequency band. The signal was amplified through the power amplifiers to a power level of 2 W. (To compensate for anticipated high chamber insertion loss, the level was raised to 4 W, from 18 to 26.5 GHz.) The level was maintained through the power meter measurements from the directional coupler at the output of the amplifier. Once the power was leveled, and after a stabilization time of approximately 1 sec, the E-Field was measured by the E-Field probe. The spectrum analyzer frequency was controlled to match the signal generator frequency during the scan. The software recorded the power level measured by the antenna and spectrum analyzer.

After the signal measurements were recorded, the signal generator and spectrum analyzer were set to the next frequency and the process was repeated through the frequency band. After recording the E-Field and power level of the last frequency in the band, the tuner was moved to the next position and the frequency sweep repeated. Once the tuner stepped through each position and frequency sweep, the software notified the Test Operator to change the sensor position. The Test Operator moved the E-Field probe and receiving antenna to their next positions. The receiving antenna was moved to a random position in the working volume at least 1 m from the previous position and changed at least 20° in each axis from its previous orientation. After completion of all probe positions in a frequency band, the data was evaluated as described in Section 5.0, Results.

4.5 Loaded Calibration

From IEC-61000-4-21, section B.1.5: “In order to determine if the chamber is adversely affected by an EUT which “loads” the chamber, perform a one-time check of the chamber field uniformity under simulated loading conditions. It is suggested the “loaded” chamber calibration be carried out only once in the life of the chamber or after major modification to the chamber.” The chamber should be loaded to at least the level expected during normal testing. The IEC specification recommends a factor of 16 reduction in Q, or 12 dB delta in Antenna Calibration Factor (ACF) as a loading goal. The ACF represents a ratio of reverberant chamber power to transmitted input power.

4.5.1 Estimate of Vehicle Loading

In February 2010, a quick-look calculation was made to determine the potential loading that the Orion CEV would present to the SET vacuum chamber. Many assumptions and data interpolations were made, with the goal of obtaining a ballpark loading value. Appendix B shows illustrations of the E-Field placements and RF equipment setups, Appendix C lists the relevant equations, Appendix D contains the CEV approximated physical characteristics used, and Appendix E contains graphs obtained from the equations using the approximated vehicle characteristics.

Once it was confirmed by completing Section 4.4 that the chamber E-Field uniformity conformed to the IEC61000-4-21 requirements for an unloaded chamber, the test was repeated with a simulated “maximum test article” load to verify that the chamber can be used with EUT while maintaining E-Field uniformity.

Loading a chamber of this size was a challenge, as few publications can be found on loading techniques with respect to Insertion Loss versus material type and quantity. Using a study by NIST from 2003,¹ it was determined that if we wanted an insertion loss of 12 dB, we needed a ratio of Q_{empty} to Q_{loaded} of 15.8. In their study, NIST used water spheres taking up ~ 0.029 percent of the experiment chamber volume, and representing 0.344 percent of the chamber Surface Area (SA) to achieve this amount of Q reduction. In addition, tests performed in a standard sized reverberation chamber (a SMART80), showed promising results with 2½ in. graphite balls and 50 lb bags of coal pieces, taking up 0.026 percent of the chamber volume and presenting 0.45 percent of the chamber SA. Figure 5 shows the loading results obtained in the Lewis Field SMART80 chamber.

The graphite consumed 0.005 percent of the chamber volume. The coal consumed 0.025 percent of the chamber volume. The graphite inhibited direct reflection across 0.14 percent of the chamber surface. The coal inhibited direct reflection across an additional 0.31 percent of the chamber surface. An analysis was performed to determine materials and quantities for a reasonable amount of loading effect in the larger PBS vacuum chamber. A combination of terminated UHF and VHF antennas, crates filled with graphite balls, pallets of coal, and 5-gal bottles of water were used as loading materials, as listed in Table 5. The total cost for loading the chamber was under \$2000.

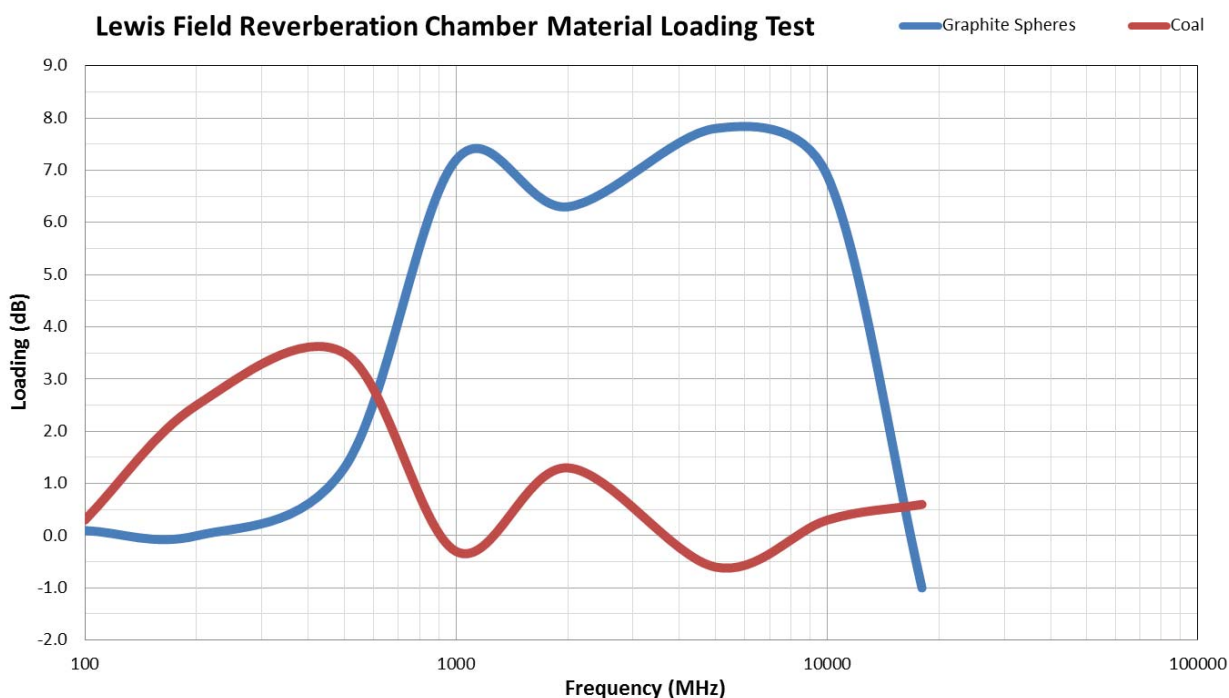


Figure 5.—SMART80 Loading Test of Graphite and Coal

¹ Christopher L. Holloway, David A. Hill, John M. Ladbury, and Todd M. Lammers, National Institute of Standards and Technology (NIST), 325 Broadway, Boulder, CO. “Assessing Loaded Reverberation Chambers: Calculating Threshold Metrics”, Electromagnetic Compatibility, 2003 IEEE International Symposium on, 2003

TABLE 5.—LOADING MATERIAL PHYSICAL PROPERTIES

Material	Volume, m ³	Surface area, m ²	Chamber volume, %	Chamber surface area, %	Target frequencies
Four VHF antennas, terminated	N/A	N/A	N/A	N/A	30 to 300 MHz
Two VHF/UHF antennas, terminated	N/A	N/A	N/A	N/A	30 MHz to 3 GHz
400 bags of coal (did not use)	2.21	0.95	0.01	1.66	100 to 700 MHz
Eleven crates, containing approximately 50,000 2.5 in. diam. graphite balls	6.7	58.25	0.029	1.016	1 to 10 GHz
500 gal of water	1.9	19.2	0.008	0.335	2.5 to 40 GHz



Figure 6.—RF Absorbing Materials in Staging Area Outside the Chamber

Due to the enormous size of the SPF vacuum chamber, and the cleanliness restrictions placed on the absorptive materials, the desired goal of 12 to 16 dB of loading was not achieved. In retrospect, the amount of materials placed in the chamber should have been greater. Looking at Figure E.4, the measured chamber loading (■) should be below the theoretical chamber/vehicle line (⊗) at all times. The actual loading obtained ranged between 3 dB at the lowest frequencies to 9 dB around 1 GHz, and back down to approximately 6 dB at the highest frequencies. Refer to Figure 14 for the graph of measured chamber loading versus frequency.

In Figure 6, the crates of graphite balls are shown on the right, and the 5-gal bottles of water are shown on the left.

The loading material was placed arbitrarily in the working volume, near the perimeter of the chamber, as shown in Figure 7. Placement of the loading material outside of the working volume is allowable per IEC 61000-4-21. In retrospect, better loading could have been achieved with the materials placed inside the working volume to expose them to more wave reflections.

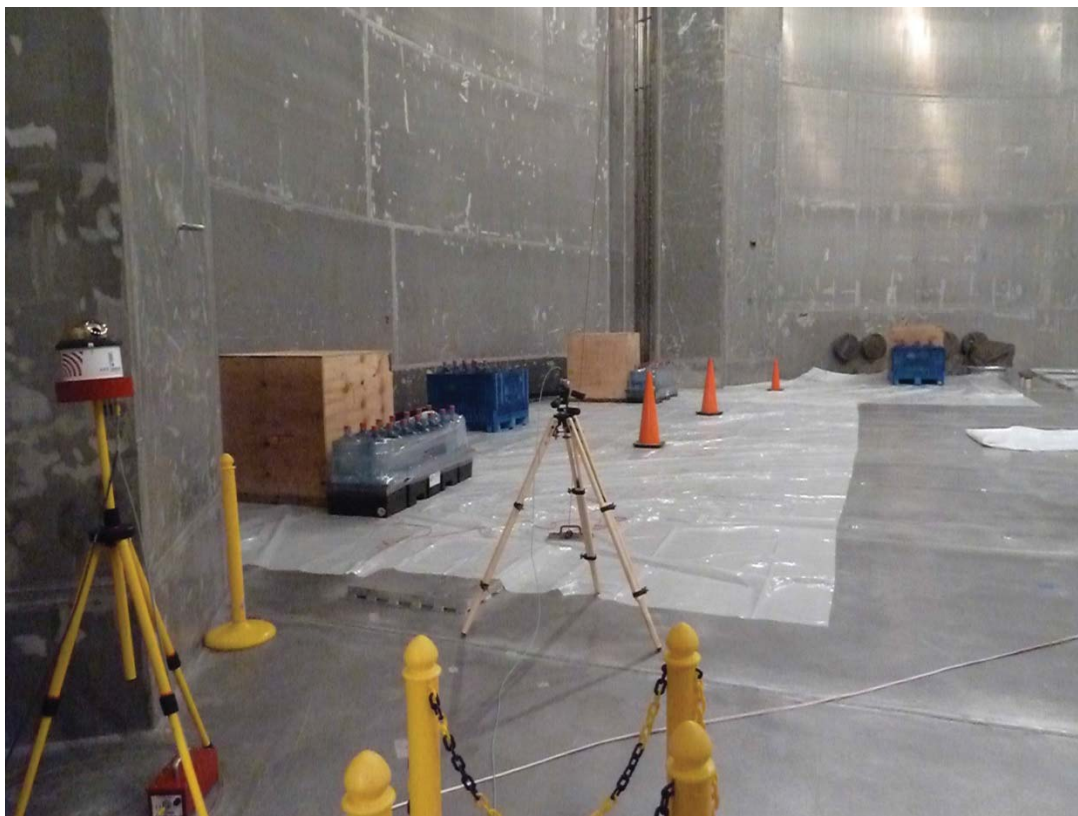


Figure 7.—Chamber Interior, Partial, Showing Graphite Ball Crates and Water Bottles

Once the loading was placed in the chamber, the calibration process in Section 4.4 was repeated and the data processed according to IEC61000-4-21, section B.1.5, and Section 5.0 of this report.

5.0 Results

5.1 Test Summary

After performing safety and equipment checkouts, the test was executed between June 30, 2011 and July 28, 2011. The test instruments were operated and data were collected by the software program EMC-32, developed by Rhode & Schwarz. The files were saved internally to the EMC-32 program, named according to Table 4 of GRC-SET-PLN-041, with the following nomenclature:

F1M₁F2M₂_XC_YYMMDDz, where

F1M₁ = F1 Start Frequency, M₁ Multiplier (M for Mega, G for Giga)

F2M₂ = F2 Finish Frequency, M₂ Multiplier (M for Mega, G for Giga)

XC = UC for Unloaded Chamber, LC for Loaded Chamber

YY = 11

MMDD = 2-digit month, 2-digit day

z = a, b, c, etc. for test re-run attempts if necessary

Testing began with the chamber in an unloaded configuration. It was soon realized that mounting the probe on a mast to achieve the highest chamber measurements was not practical. Refer to Figure 8 for a picture of the mast in its extended position. The support structure was redesigned to utilize a helium-filled

balloon to raise the probe to the desired height. It was found that the air inside the chamber was still enough to allow for very stable positioning with guy wires. In addition, a greater height was achievable with this design, 23 m (76 ft) instead of 18 m (58.5 ft). See Figure 9 to see the filling process and final configuration for the helium balloon probe support design.

The original test plan, presented in GRC-SET-PLN-041, Appendix A, was also altered during the test. This was to account for the updated chamber configuration layouts, probe locations, and paddle positions, as shown in Table 6.

TABLE 6.—TEST SUMMARY

Unloaded Chamber									
Test dates	^a Frequency	Calibration layout diagram	Probe positions	Tuner positions	Scan time per probe position (min)	Total scan time (hr)	Setup time (min per probe position)	Total setup time (hr)	Reconfiguration time (hr)
7/11 - 7/12	100 to 300 (50)	P1	11	50	85	15.58	15	2.75	1
7/11 - 7/13	100 to 300 (20)	P2	7	20	45	5.25	15	1.75	0
6/30 - 7/15	300 to 1000	P3	18	18	40	12.00	15	4.5	1
6/30 - 7/5	300 to 1000	P4	5	18	40	3.33	15	1.25	1
7/6 - 7/13	1000 to 4000	P5	10	12	20	3.33	15	2.5	1
7/6 - 7/13	4000 to 8000	P5	10	12	20	3.33	15	2.5	1
7/7 - 7/14	8000 to 18000	P5	10	12	20	3.33	15	2.5	1
7/7 - 7/14	18 to 26	P5	10	12	20	3.33	15	2.5	1
7/8 - 7/14	26 to 40	P5	10	12	20	3.33	15	2.5	1
-----	-----	--	--	--	--	52.8333333	--	22.75	8
Total			7 days(12 hr days)						
Loaded Chamber									
Test dates	^a Frequency	Calibration layout diagram	Probe positions	Tuner positions	Scan time per probe position (min)	Total scan time (hr)	Setup time (min per probe position)	Total setup time (hr)	Reconfiguration time (hr)
7/26 - 7/28	100 to 300 (50)	P6	11	50	85	15.58	15	2.75	1
N/A	100 to 300 (20)	P6	7	20	45	5.25	15	1.75	0
7/22 - 7/26	300 to 1000	P6	18	18	40	12.00	15	4.5	1
7/21	1000 to 4000	P6	10	12	20	3.33	15	2.5	1
7/20 - 7/21	4000 to 8000	P6	10	12	20	3.33	15	2.5	1
7/20	8000to 18000	P6	10	12	20	3.33	15	2.5	1
7/19	18 to 26	P6	10	12	20	3.33	15	2.5	1
7/18 - 7/19	26 to 40	P6	10	12	20	3.33	15	2.5	1
-----	-----	--	--	--	--	49.5	--	21.5	7
Total			6.5 days (12 hr days)						

^aFrequency is in MHz through 18,000, then switches to GHz for the last two rows (18 – 26 and 26 – 40)



Figure 8.—Measurement Probe Mounted to Mast Support

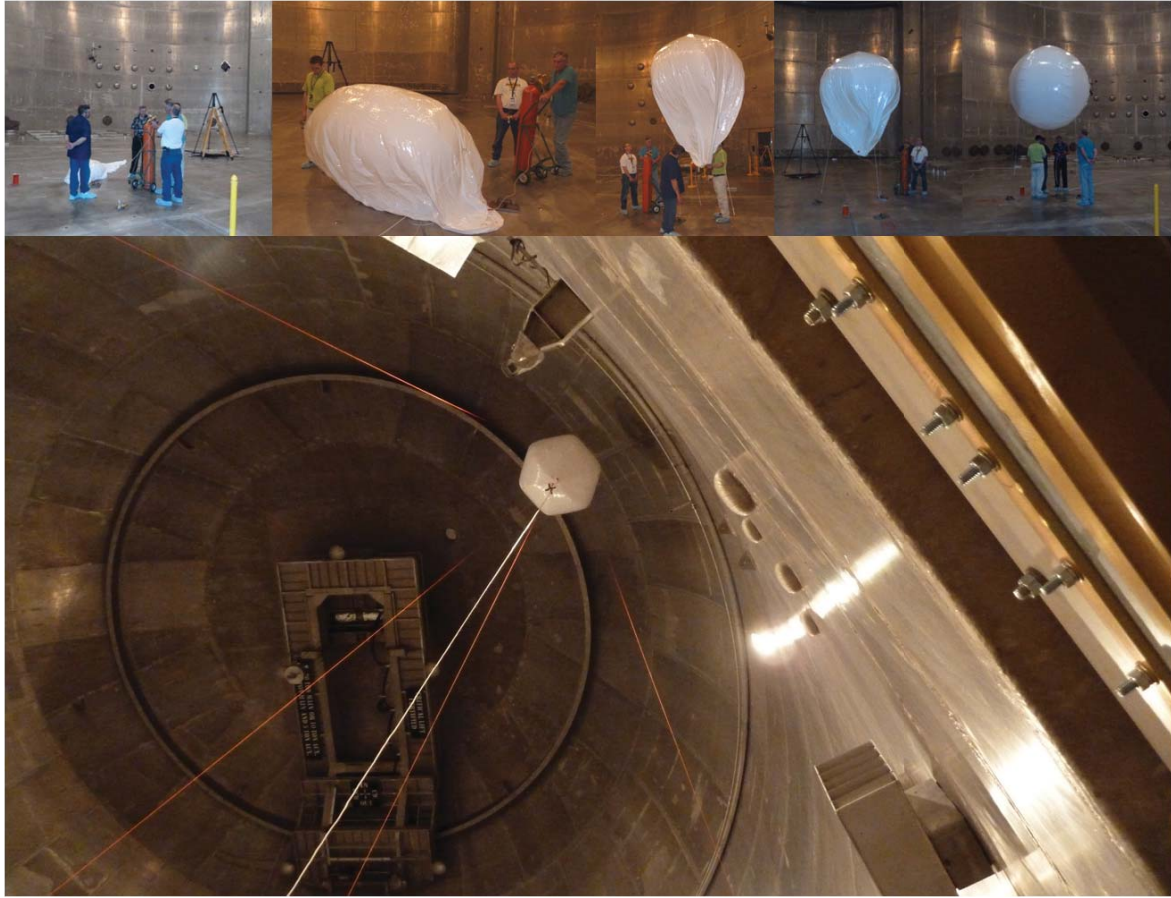


Figure 9.—Filling Process and Deployment of Measurement Probe Mounted to Helium Balloon

5.2 Chamber Uniformity, Unloaded

At the end of testing all of the frequency bands in the unloaded configuration, the program EMC-32 created a summary file, taking the appropriate value from each of the many files and placing it in a summary table in order to calculate field uniformity. Verification of the program's methodology can be found in Section 6.0, EMC-32 Data Verification and Validation. Referencing Figure 10, it can be seen that the chamber uniformity meets the criteria specified in IEC-61000-4-21, Table B.2, for all frequencies between 100 MHz and 40 GHz in the unloaded configuration.

5.3 Chamber Uniformity, Loaded

The chamber was loaded with a combination of RF absorbing materials to obtain as much loading as possible while complying with the chamber's unique cleanliness (vacuum) requirements. Terminated antennas, graphite balls, and water were used to cover the test frequency spectrum. For more detailed information about the loading calculations and material arrangement, refer to Section 5.5, Chamber Loading. The Chamber uniformity with the loading materials installed is shown in Figure 11.

The graph in Figure 11 shows 3 points in the Y direction, and 3 points in the Z direction that are above the limit. The specification states that "a maximum of three frequencies per octave may exceed the allowed standard deviation by an amount not to exceed 1 dB of the required tolerance". The over-limit points contain only 2 within one octave, therefore the "frequencies per octave" uniformity requirement was met for all individual axes plus the XYZ composite. In addition, the maximum value is 0.234 dB over the limit, meeting the amplitude requirement. In summary, the field uniformity requirement in 61000-4-21, section B.1.1 was met.

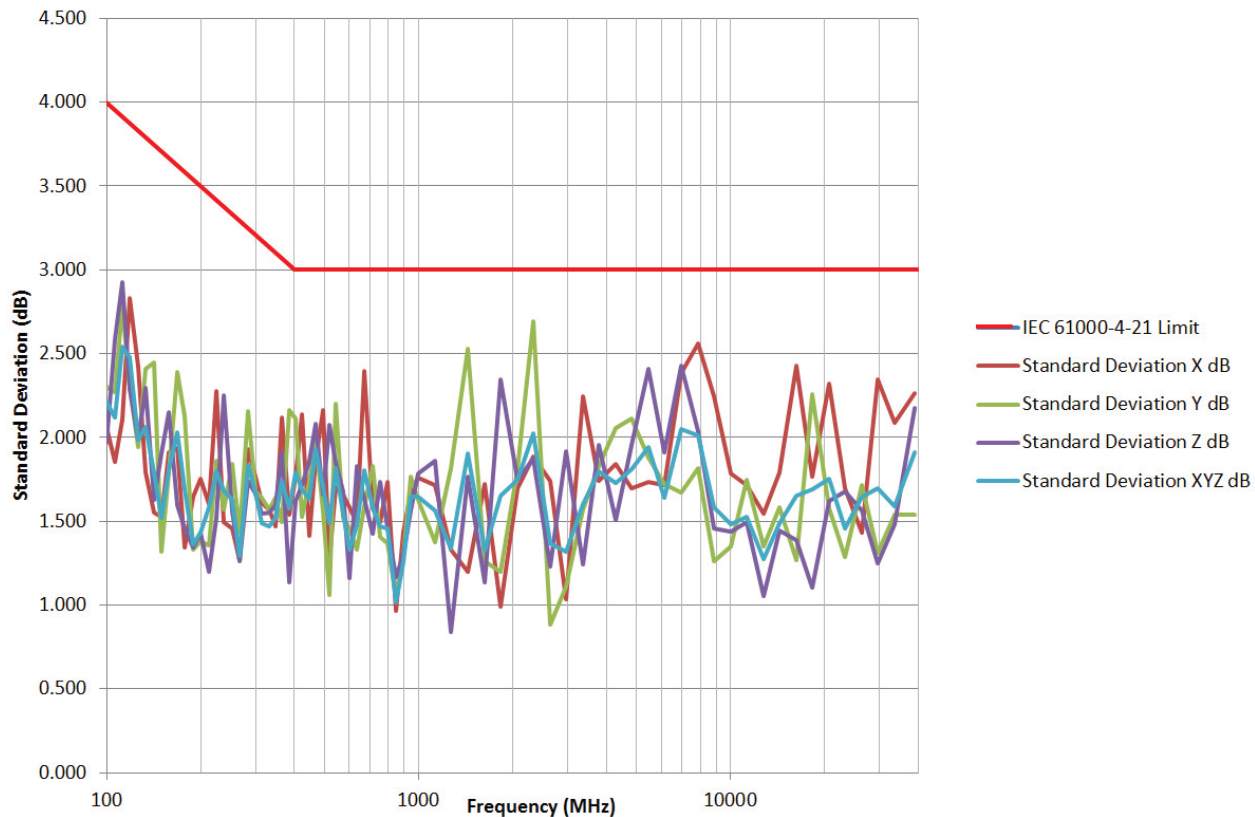


Figure 10.—Chamber Uniformity in the Unloaded Configuration

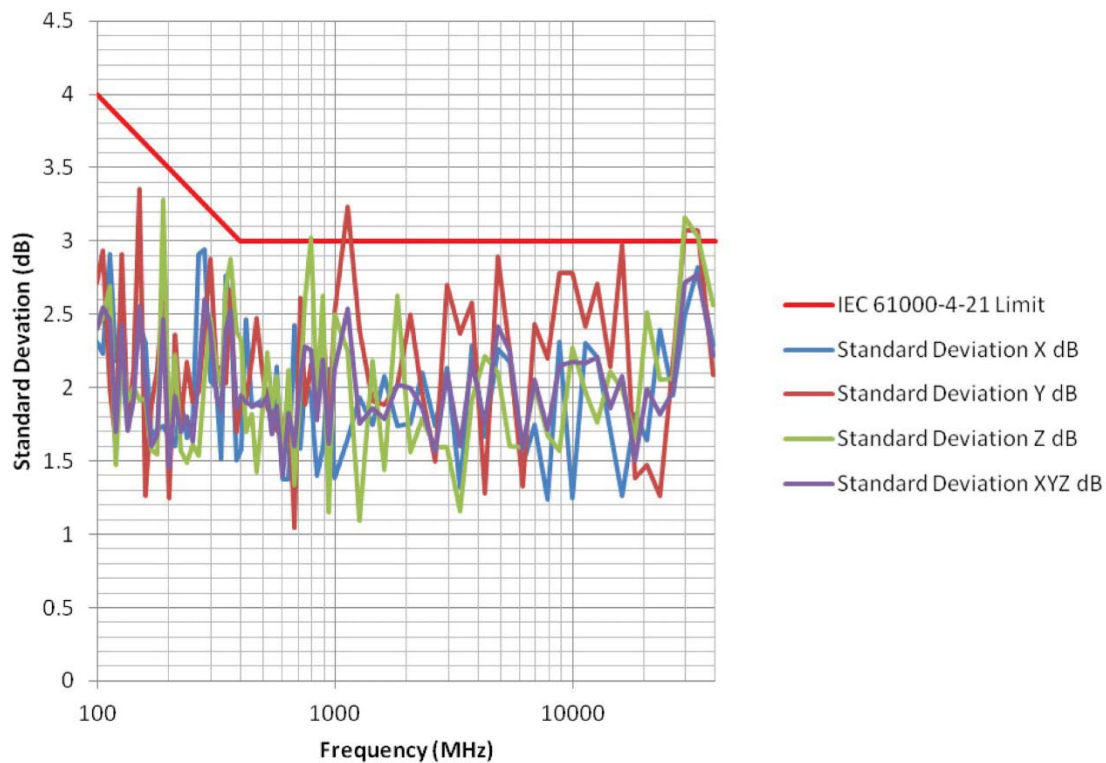


Figure 11.—Chamber Uniformity in the Loaded Configuration

5.4 Antenna Calibration Factor (ACF)

The receiving ACF is determined as an intermediary step to allow the calculation of chamber loading, and is shown in Figure 12 and Figure 13. It is defined as the ratio of the average received power to the average input power, averaged over the measurement locations and paddle positions. The ACF ratio is calculated with linear power (Watts), and is always less than one. Hence, when converted to decibels, the value is always negative. Many times the ACF in decibels is graphed as an absolute value, with the understanding that it is a “loss”, and the negative property is understood.

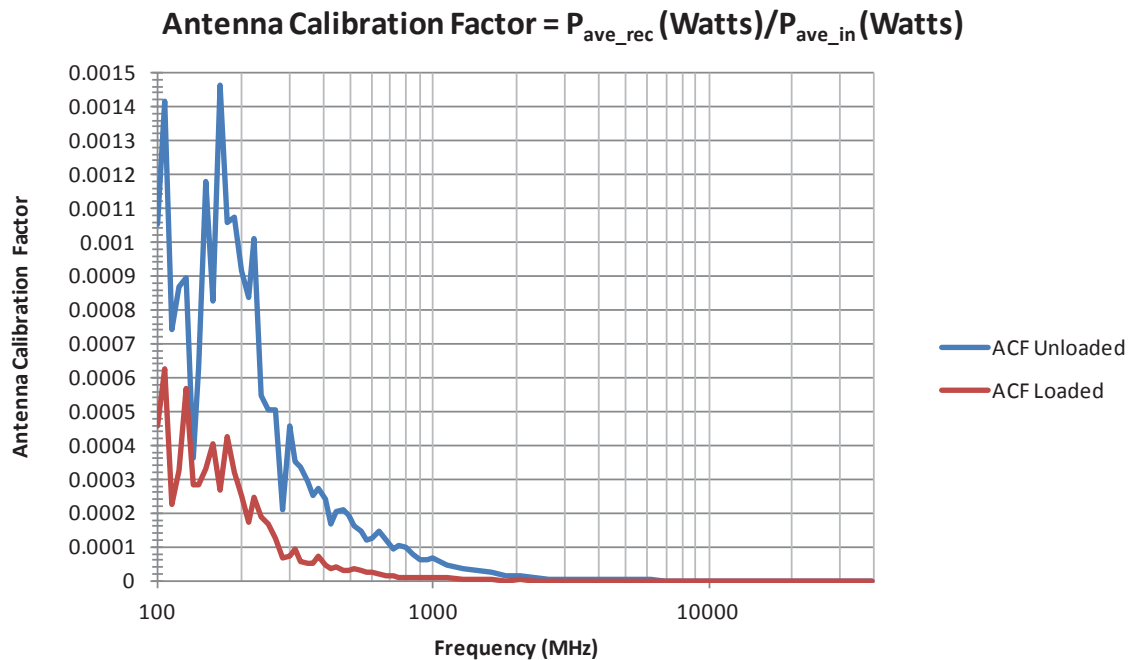


Figure 12.—Antenna Calibration Factor (ACF), Linear

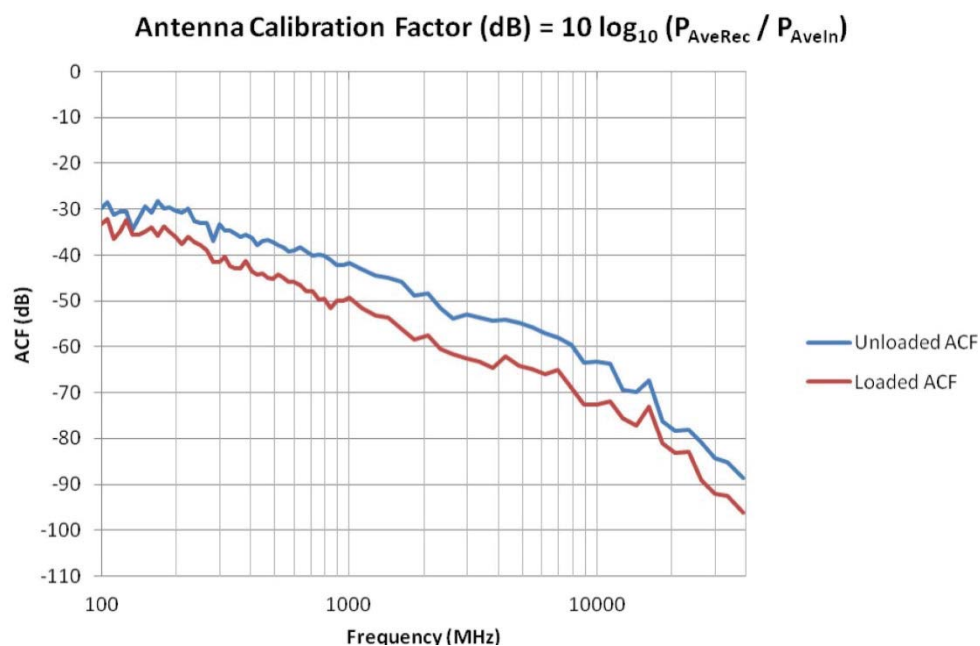


Figure 13.—Antenna Calibration Factor (ACF), in decibels

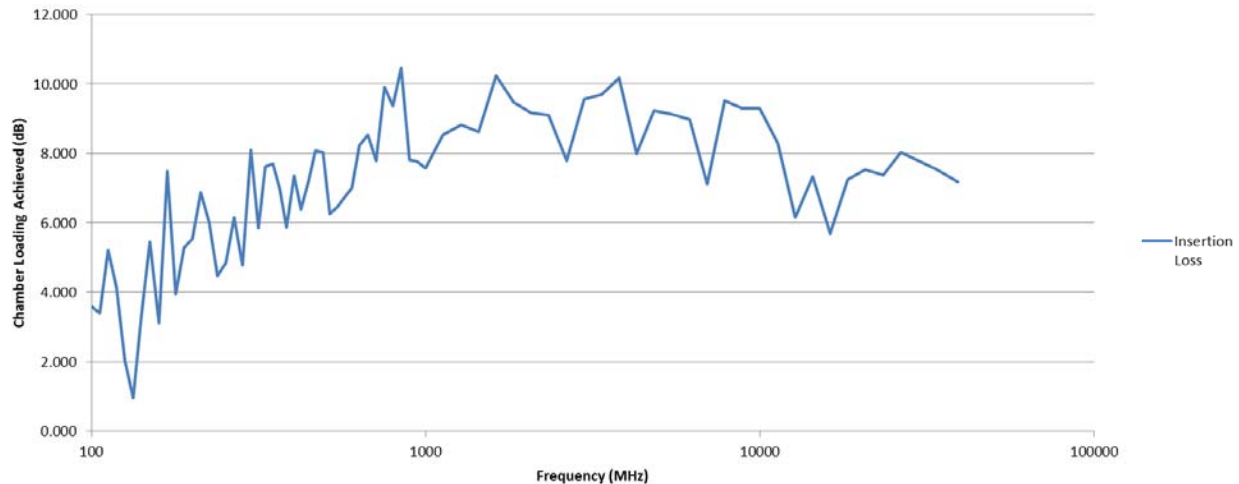


Figure 14.—Chamber Loading Achieved During Chamber Calibration

5.5 Chamber Loading

The chamber loading is calculated in decibels. The purpose of this calculation is to show that with the loading achieved at a given frequency, the chamber field uniformity requirement is met. We showed that the uniformity was met for the loading shown in Figure 11 in Section 5.3. When a test article wishes to use this facility, the EUT and its support equipment are placed in the chamber. Then the average received power at one probe location and the required tuner steps is used to calculate the loading provided by the EUT and support equipment. If the loading exceeds the values shown in Figure 14, then there is the possibility that the chamber may be loaded to the point where field uniformity is affected. In such a case, the chamber uniformity measurements outlined in IEC-61000-4-21, section B.1.1 must be repeated with the EUT in place or with a simulated load equivalent to the EUT.

5.6 Chamber Insertion Loss

The chamber insertion loss provides information necessary for other calculations. It is defined as the average, over the antenna locations, of the ratio of the maximum power received to the average input power. The power unit used for this calculation must be in Watts. Once calculated in a linear fashion, the insertion loss can be converted to decibels by taking its base 10 log and multiplying by 10. Figure 14 and Figure 15 show the linear insertion loss, and Figure 16 shows the log based insertion loss. The data obtained during this chamber calibration test differs from the data taken by NIST in 2009 by a factor of ~100 (20 dB), as shown in Figure 17.

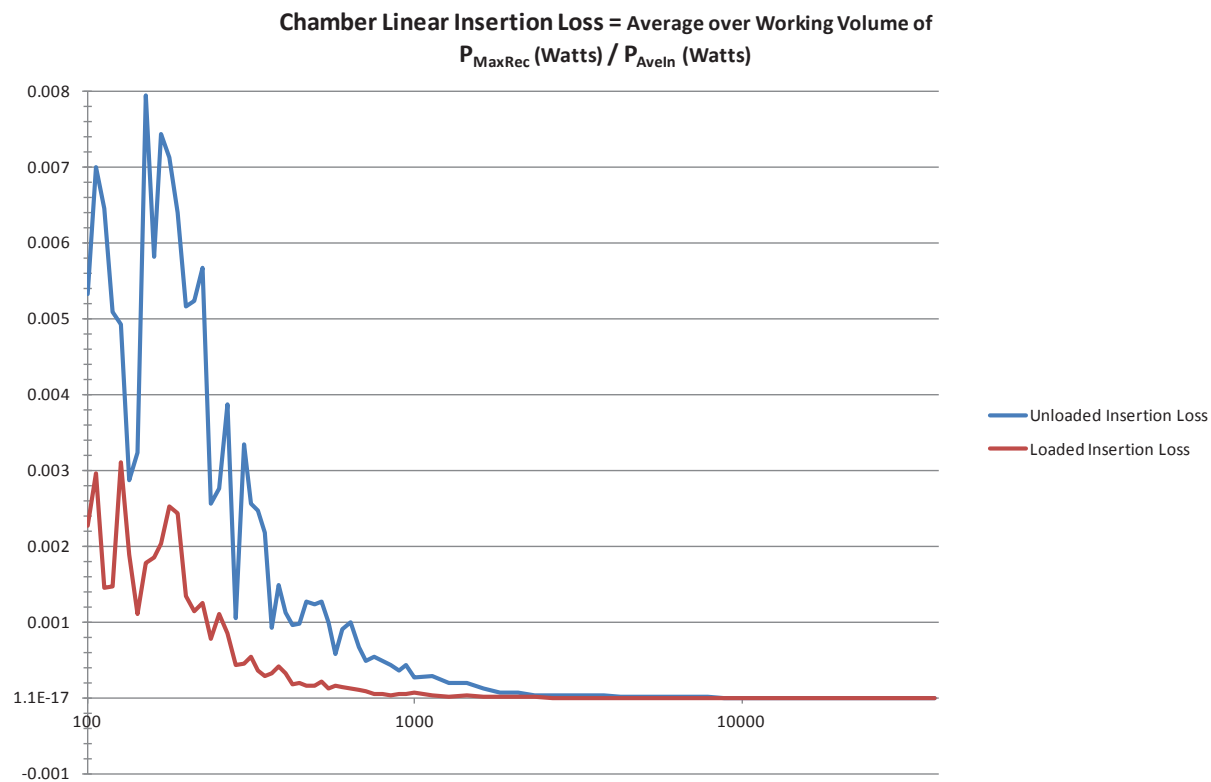


Figure 15.—Linear Insertion Loss for Empty and Loaded Chamber

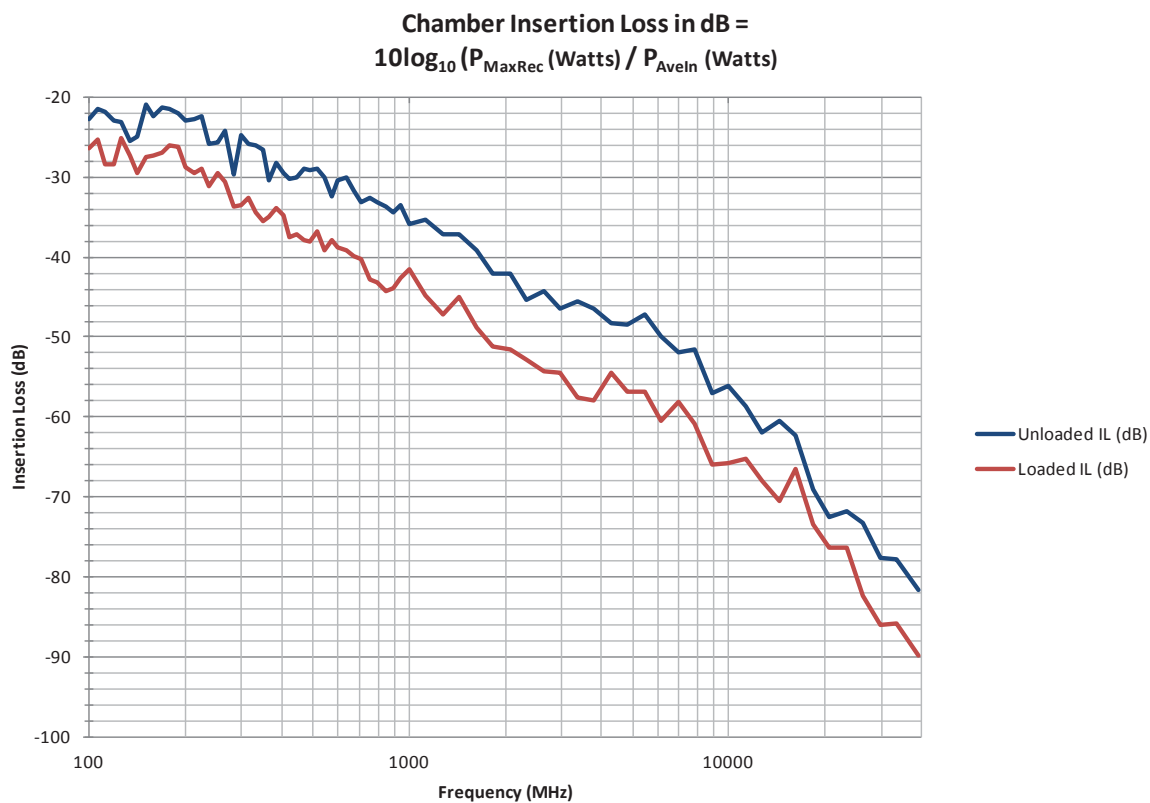


Figure 16.—Chamber Insertion Loss Expressed in decibels

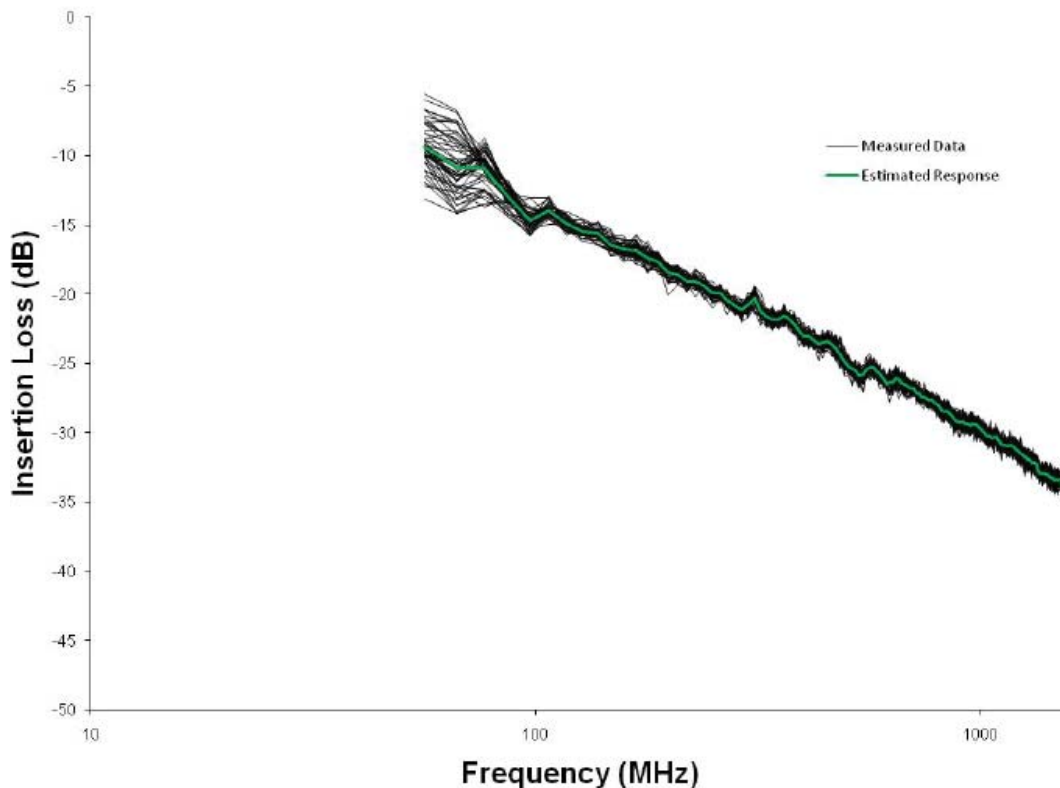


Figure 17.—NIST Measured Insertion Loss

5.6.1 Chamber Quality Factor

The calculation of chamber Q performed internal to EMC-32 originally differed from the calculations based on the below formulas for Q and $Q_{\text{Threshold}}$:

$$Q = \frac{16\pi^2 V P_{\text{AveRec}}}{\lambda^3 P_{\text{Input}}} \qquad Q_{\text{Threshold}} = \frac{[4\pi/3]^{2/3} V^{1/3}}{2\lambda}$$

where

V = Chamber Volume = 23426 m³

Throughout the course of 2011 and 2012, it was discovered that the data reduction resident in EMC-32 contained errors. Once the errors were corrected and the raw data was run through the reduction algorithm, the measured/calculated Q values correlated quite nicely with those obtained by NIST in 2009.

In addition to the difference between the hand calculations and the values provided by EMC-32 for the Q data, there was a block of data between 300 MHz and 1 GHz that seemed to have a Q calculation error within the EMC-32 output. It is believed that an attenuation factor was not input correctly at the time of the measurements, causing the numbers to be off. The graph of the Unloaded Chamber Q in Figure 18 contains a correction in this frequency band, based on the shape of the Q curve of the loaded chamber. This was also corrected by Rhode & Schwarz. Figure 19 compares the data obtained in this test compared to the data obtained by NIST.

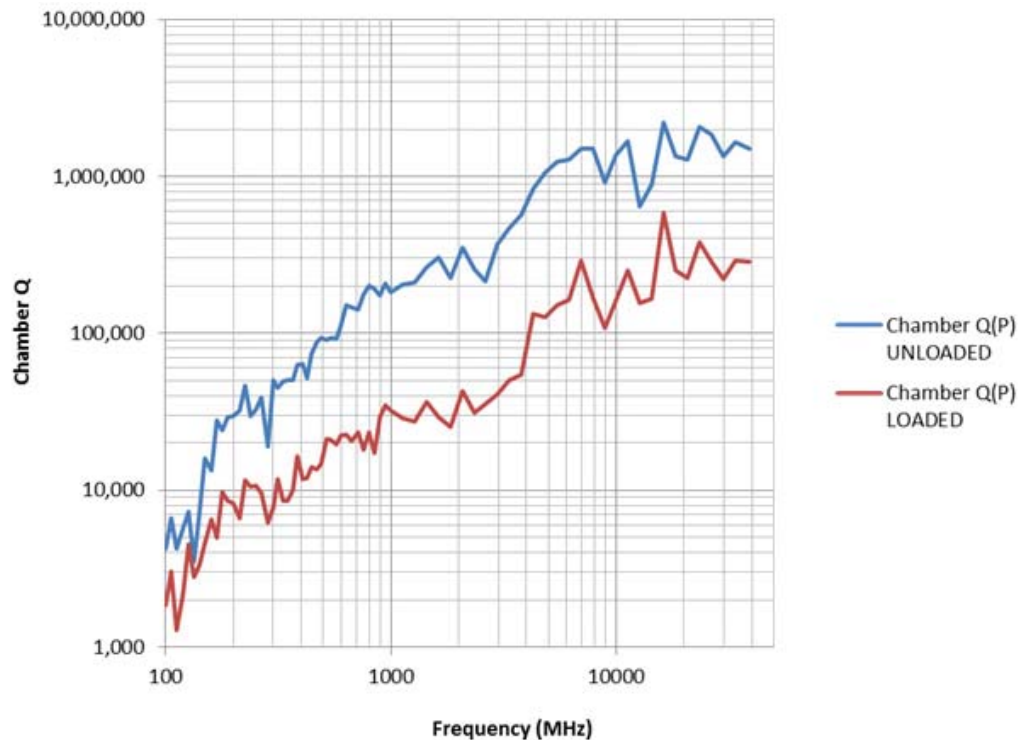


Figure 18.—Chamber Q Values Calculated from Test Data

Empty Chamber Q Calculated by NIST in 2009 Compared with Empty and Loaded Q Calculated by NASA from Measurements Taken in 2011

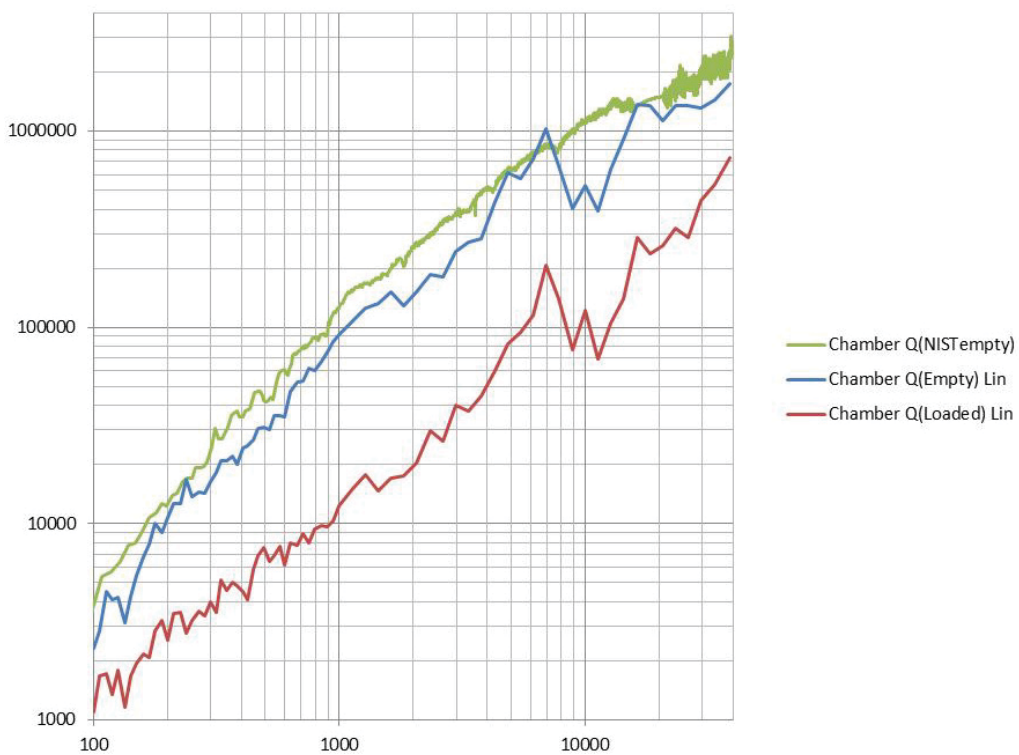


Figure 19.—Chamber Q: Unloaded, Loaded, and NIST (2009)

SPF at Plum Brook Station Reverb Chamber E-Field Generation Capability with 2011 E3 Equipment

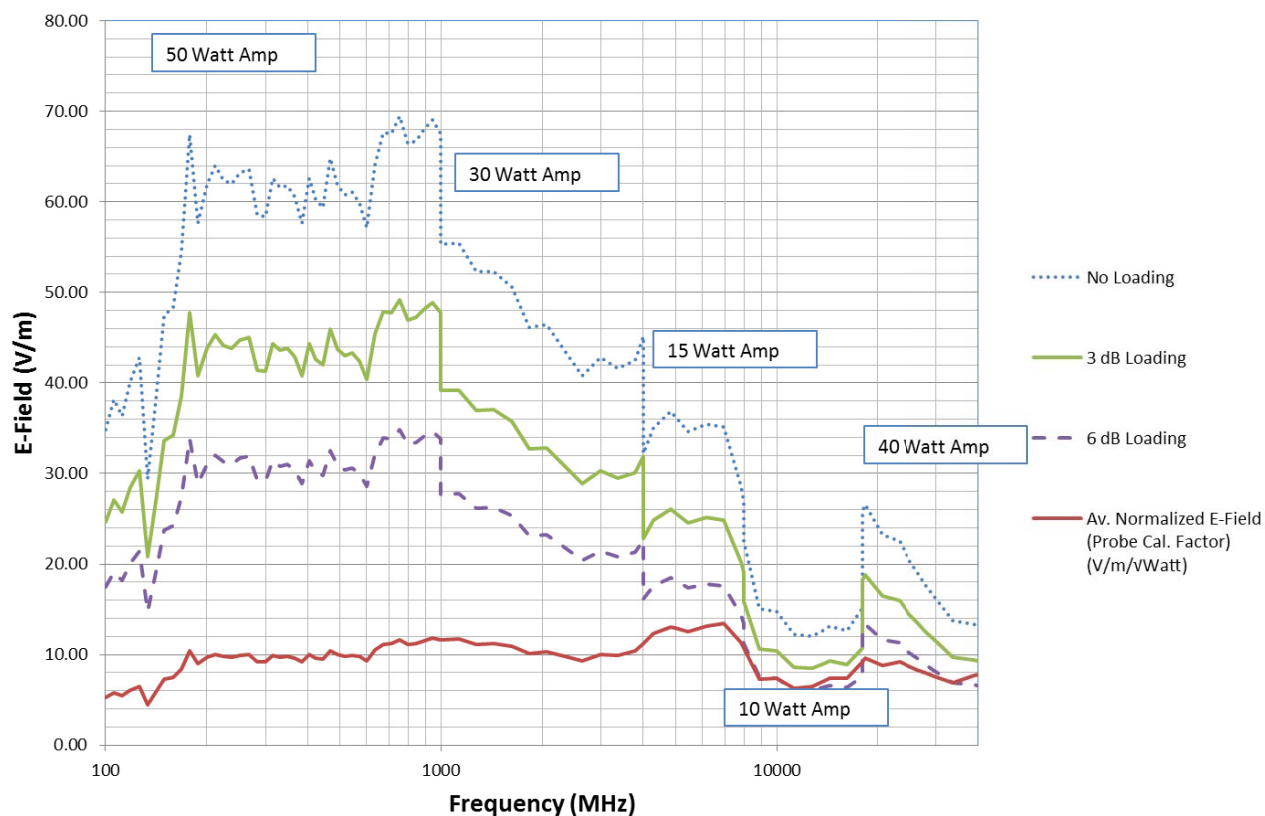


Figure 20.—Calculated E-Fields Possible with 2011 Equipment

5.7 Calculations of E-Fields Possible with 2011 Equipment

With the equipment described in Section 3.3, the E-Fields possible with various loads was calculated, as shown in Figure 20.

5.8 Calculated Power Required for 200 V/m E-Field

To obtain the target 200 V/m field required by NASA EMC test specifications, the required amplifier output is shown in Figure 21, calculated using the following formula:

$$\text{Amplifier Output (W)} = \left(\frac{\text{Target Field} \left(\frac{\text{V}}{\text{m}} \right)}{\text{Probe Cal Factor} \left(\frac{\text{V}}{\text{m}} \sqrt{\text{W}} \right) * \sqrt{\text{Chamber Loading Factor}}} \right)^2$$

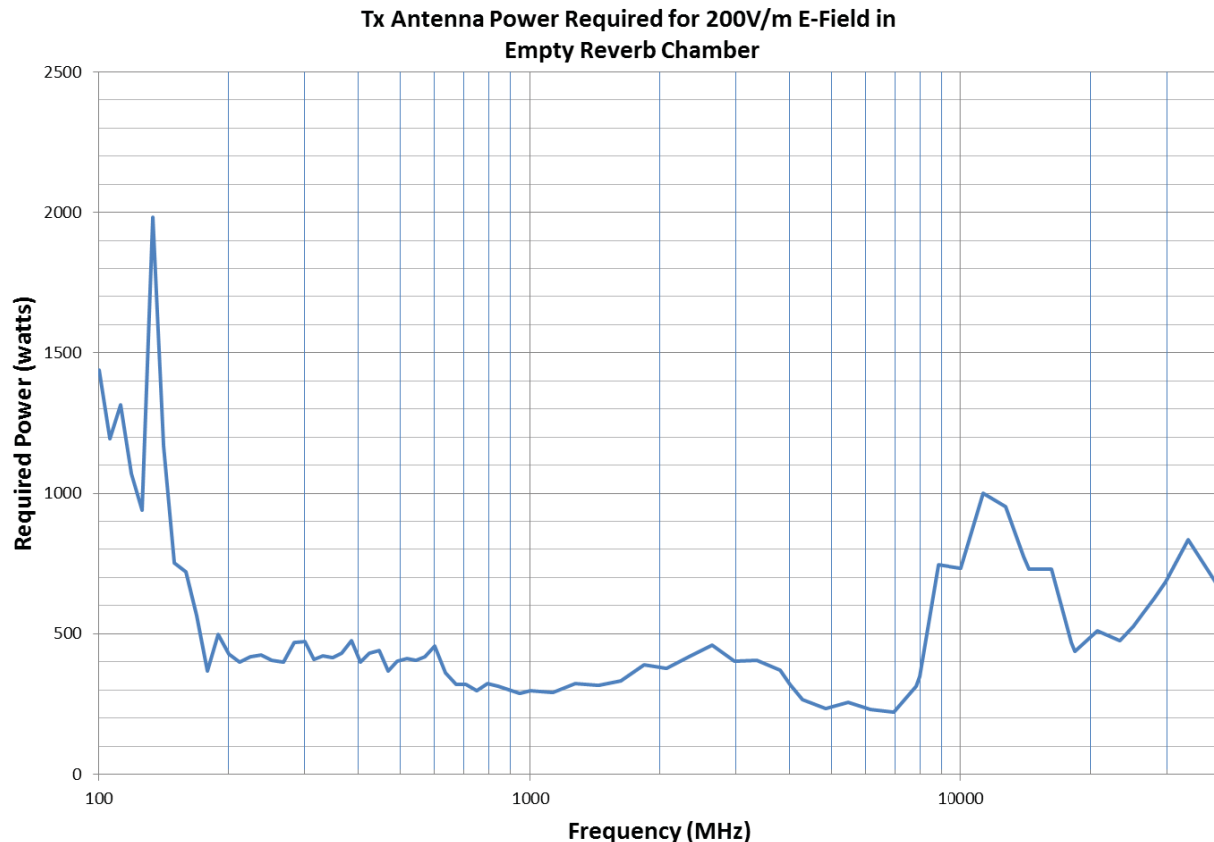


Figure 21.—Calculated Transmit Power Required to Generate 200 V/m E-Field

6.0 EMC-32 Data Verification and Validation

To ensure that the methodology of data manipulation within EMC-32 was understood, a subsection of data, taken at frequencies between 8 and 18 GHz, was verified. The process involved the following steps:

1. Open and export 120 files as Microsoft Excel (Microsoft Corporation) spreadsheets, corresponding to the 10 probe positions and 12 paddle positions measured at this frequency band.
2. For each of the 120 files, at each of the **6 frequencies**, take the X, Y, and Z measured E-Field (V/m) sensor level and place it into a spreadsheet cell. (120 measurement columns by 6 frequencies)
3. For each **probe position**, find the maximum E-Field and normalize it by the square root of the input power. (10 probe position columns by 6 frequencies)
4. Find the MEAN of the maximums from Step 3. (1 column by 6 frequencies)
5. Subtract the Mean, obtained in Step 4, from the normalized maximum obtained in Step 3, and square the resulting value. (10 probe positions by 6 frequencies)
6. Add the 10 values per frequency, obtained in 5, together. Divide by 9, and take the square root to obtain the normalized standard deviation, relative to the normalized mean value. Multiply this value by 1.06, according to the directions in IEC61000-4-21. (9 represents the number of probe positions minus 1)
7. Add the standard deviation obtained in Step 6 to the normalized mean value obtained in Step 4, divide by the mean value from Step 4, and convert to decibels by taking the $\log(10)$ of the resulting value and multiplying by 20. (The multiplier is 20 because the measurement units are volts per meter.)

Steps 3 to 7 were repeated to obtain X-axis, Y-axis, Z-axis, and XYZ composite field confirmation. The X, Y, and Z were verified within rounding error. The XYZ composite was close but not exact. It is suspected that the difference lies in the author's understanding of the vector calculation. In Table 7, the calculations for the X-axis are shown. Table 8 shows the calculations for X, Y, and Z axes, and the composite XYZ, compared to the values provided by EMC-32 software. The like-colored columns should be compared. The frequencies between 26.5 GHz and 40 GHz were analyzed as above for further verification and validation, and the results are also shown in Table 8.

The values used in Table 7, and those obtained for the Y and Z axes, were used for all subsequent calculations (EMC, Chamber Loading, Insertion Loss, and Chamber Q). By verifying the software's calculation of field uniformity, the other calculations were quickly verified to be accurate as well.

TABLE 7.—X-AXIS STANDARD DEVIATION VERIFICATION CALCULATIONS

Frequency (MHz)	Probe position									
	1	2	3	4	5	6	7	8	9	10
Maximum X-component of the e-field at each probe position, normalized to the square root of the input power										
8858.670000	6.500	4.905	7.136	5.764	6.442	5.660	6.674	9.472	9.389	11.251
10000.000000	5.615	7.014	6.419	7.039	6.929	10.058	7.653	10.131	7.394	10.341
11288.380000	6.425	4.843	6.907	6.966	6.301	3.295	6.437	6.168	7.917	6.774
12742.750000	6.455	6.869	6.625	6.987	6.342	3.651	4.560	6.475	7.061	6.599
14384.500000	7.108	7.043	5.802	6.603	6.447	11.324	7.557	8.630	6.074	7.332
16237.770000	7.146	7.134	5.996	5.306	6.952	3.587	9.898	7.738	11.513	7.926
Normalized mean value of the max values of the x-component of the e-field										
8858.670000	7.319									
10000.000000	7.859									
11288.380000	6.203									
12742.750000	6.162									
14384.500000	7.392									
16237.770000	7.320									
Squared (normalized max minus normalized mean)										
8858.670000	0.672	5.829	0.034	2.418	0.770	2.754	0.417	4.636	4.286	15.456
10000.000000	5.036	0.714	2.075	0.673	0.866	4.835	0.043	5.159	0.216	6.158
11288.380000	0.049	1.851	0.496	0.581	0.009	8.459	0.055	0.001	2.936	0.325
12742.750000	0.085	0.499	0.214	0.680	0.032	6.306	2.567	0.098	0.807	0.191
14384.500000	0.081	0.122	2.527	0.623	0.893	15.458	0.027	1.533	1.738	0.004
16237.770000	0.030	0.034	1.751	4.055	0.135	13.931	6.647	0.175	17.583	0.367
Normalized standard deviation of the x-component, relative to the normalized mean value										
8858.670000	2.034991477	2.157								
10000.000000	1.692315592	1.794								
11288.380000	1.280713479	1.358								
12742.750000	1.129399861	1.197								
14384.500000	1.598838541	1.695								
16237.770000	2.228812049	2.363								
Expressed in decibels, normalized standard deviation of the C-component, relative to the normalized mean value										
8858.670000	1.058	2.243								
10000.000000	0.973	1.786								
11288.380000	0.932	1.719								
12742.750000	0.922	1.542								
14384.500000	0.837	1.793								
16237.770000	1.128	2.430								

Not shown: E-Field Sensor Level Data, X-axis, for 12 Paddle positions and 10 Probe locations

TABLE 8.—COMPARISON OF CALCULATED VALUES (RIGHT) WITH EMC-32 VALUES (LEFT)

Frequency	x std dev	y std dev	z std dev	xyz std dev	x STD DEV	y STD DEV	z STD DEV	xyz STD DEV
	EMC 32				V&V			
8858.67	2.242	1.262	1.459	1.586	2.243	1.263	1.459	1.588
10000.00	1.786	1.350	1.441	1.480	1.786	1.350	1.439	1.490
11288.38	1.717	1.746	1.496	1.529	1.719	1.749	1.499	1.438
12742.75	1.543	1.350	1.056	1.277	1.542	1.351	1.058	1.016
14384.50	1.794	1.586	1.442	1.489	1.793	1.584	1.443	1.702
16237.77	2.429	1.270	1.388	1.651	2.430	1.271	1.389	1.626
29763.51	2.344	1.250	1.250	1.696	2.342	1.3093	1.250	1.737
33598.18	2.089	1.480	1.480	1.592	2.086	1.5409	1.480	1.173
39000.00	2.263	2.174	2.174	1.909	2.268	1.5458	2.173	2.085

7.0 Conclusion

The SPF E3 Chamber was calibrated, according to the specifications contained in IEC 61000-4-21. The data shows that the standard deviation of the field in each axis and composite XYZ meets the uniformity requirement. In addition, the loaded chamber meets the same uniformity requirement. The chamber is therefore certified for reverberation method testing, as long as the EUT loads the chamber less than the frequency dependent values shown in Figure 14.

Appendix A.—Acronyms

ACF	Antenna Calibration Factor
CEV	Crew Exploration Vehicle
CM	Crew Module
E3, E ³	Electromagnetic Environmental Effects
EM	electromagnetic
EMC	electromagnetic compatibility or control
EMI	electromagnetic interference
EUT	equipment under test
FCC	Federal Communications Commission
GRC	NASA Glenn Research Center
GSHMS	Glenn Safety and Health Management System
LAS	Launch Abort System
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NPR	NASA Procedural Requirements
NTIA	National Telecommunications and Information Administration
OME	Outer Main Engine
OML	Outer Mold Line
PBS	Plum Brook Station
RF	radio frequency
SE	shielding effectiveness
SET	Space Environmental Test
SM	Service Module
SPF	Space Power Facility
SRD	System Requirements Document
TBD	to be determined
V/m	volts per meter, electric field strength
μV/m	microvolts per meter, electric field strength

Appendix B.—Illustrations of E-field Probe Placement and RF Equipment Setups

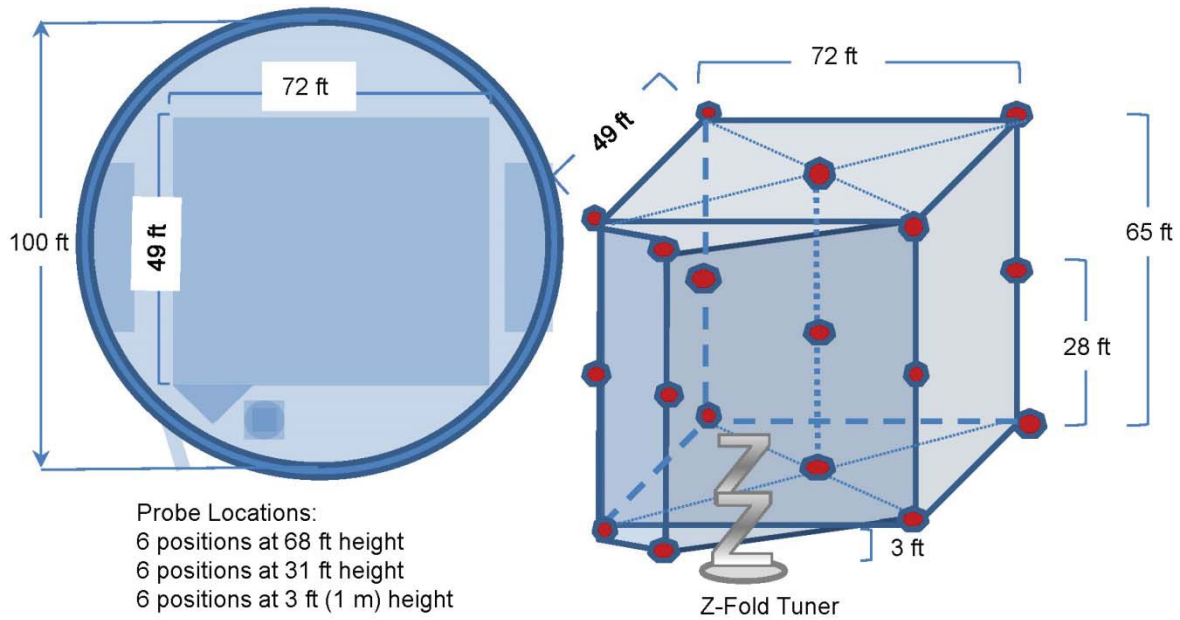


Figure B.1.—Generic Placement for 18 Probe Measurements Defining the Working Volume

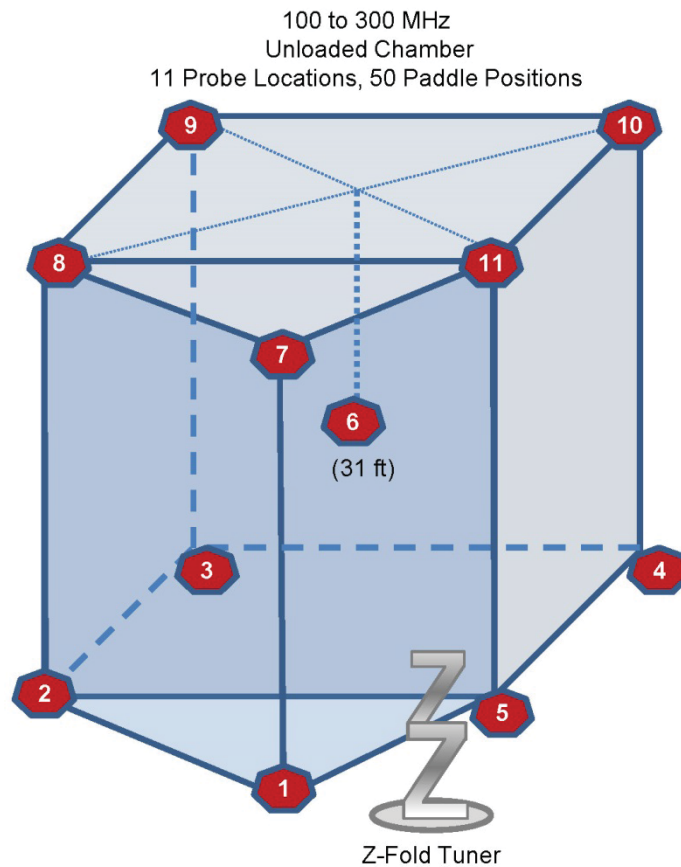
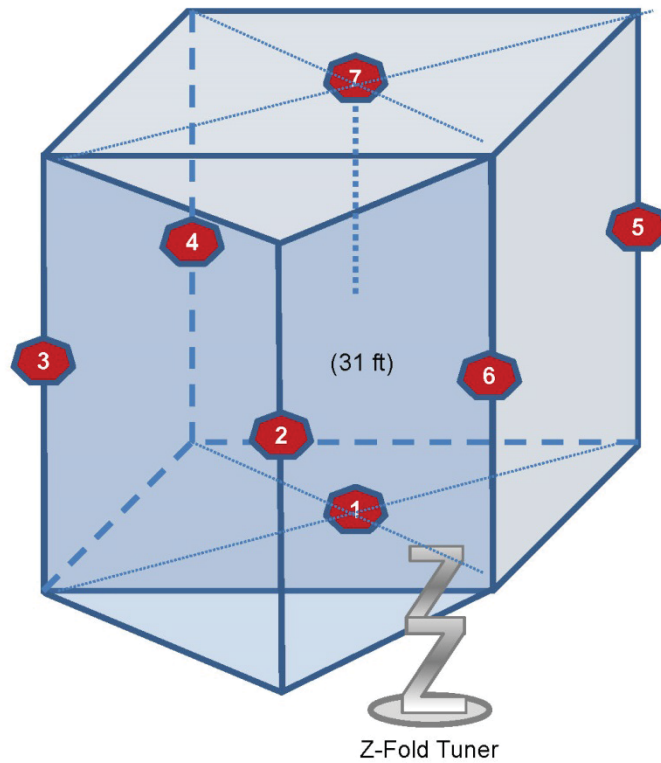


Figure B.2.—Probe Placement Configuration P1

100 to 300 MHz
Unloaded Chamber
7 Probe Locations, 20 Paddle Positions



Note 1: Position 1 is at center of chamber

Note 2: Position 7 is not at center of chamber, as crane would interfere with helium balloon (needed 2 to 3 ft off-center clearance)

Figure B.3.—Probe Placement Configuration P2

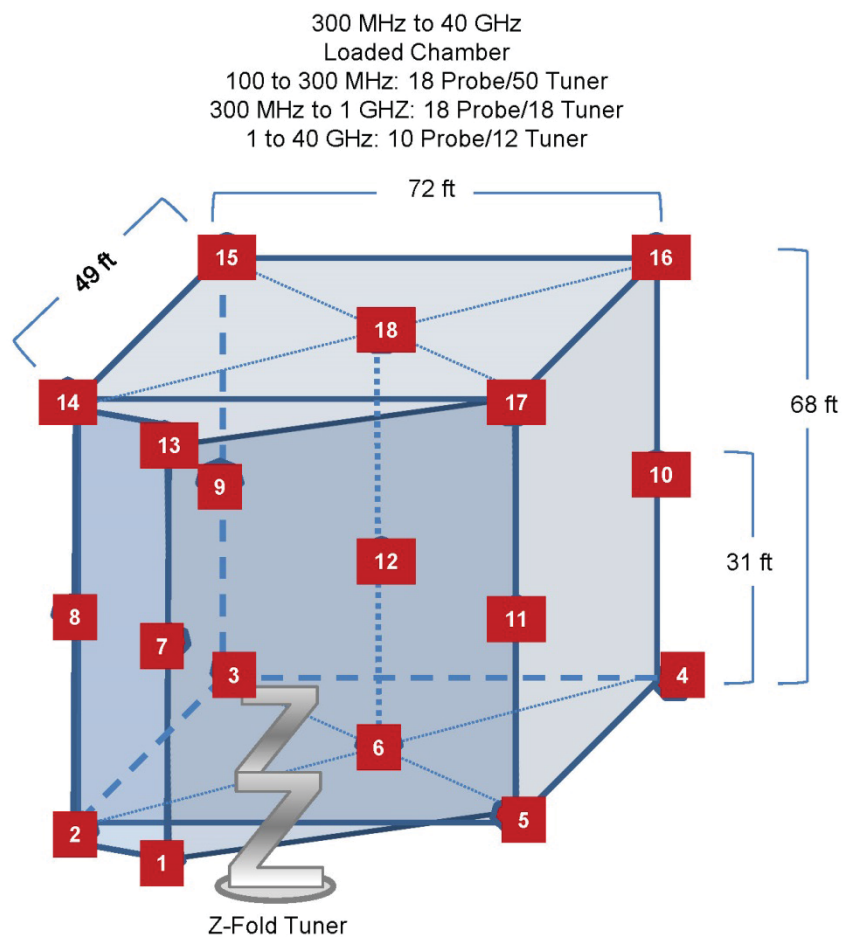
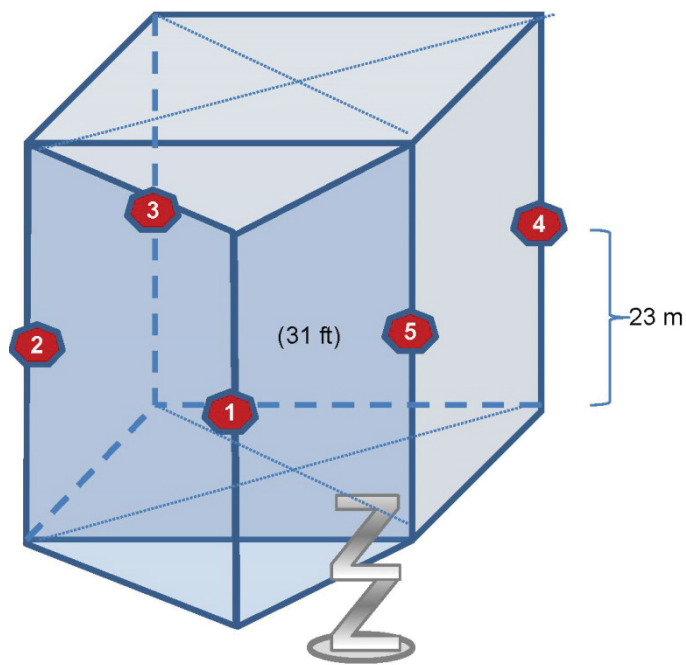


Figure B.4.—Probe Placement Configuration P3

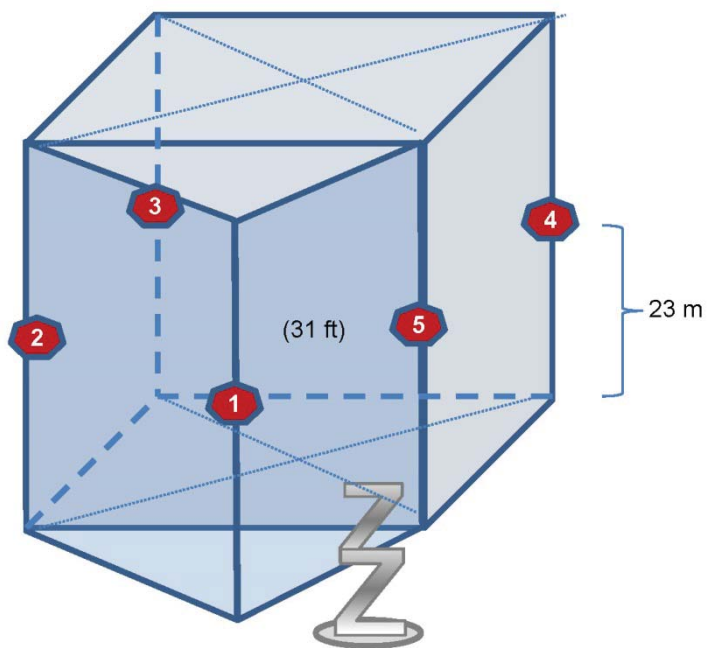
300 MHz to 1 GHz
Unloaded Chamber, Test 2 of 2
5 Probe Locations



Z-Fold Tuner

Figure B.5.—Probe Placement Configuration P4

1 to 40 GHz
5 Probe Locations



Z-Fold Tuner

Figure B.6.—Probe Placement Configuration P5

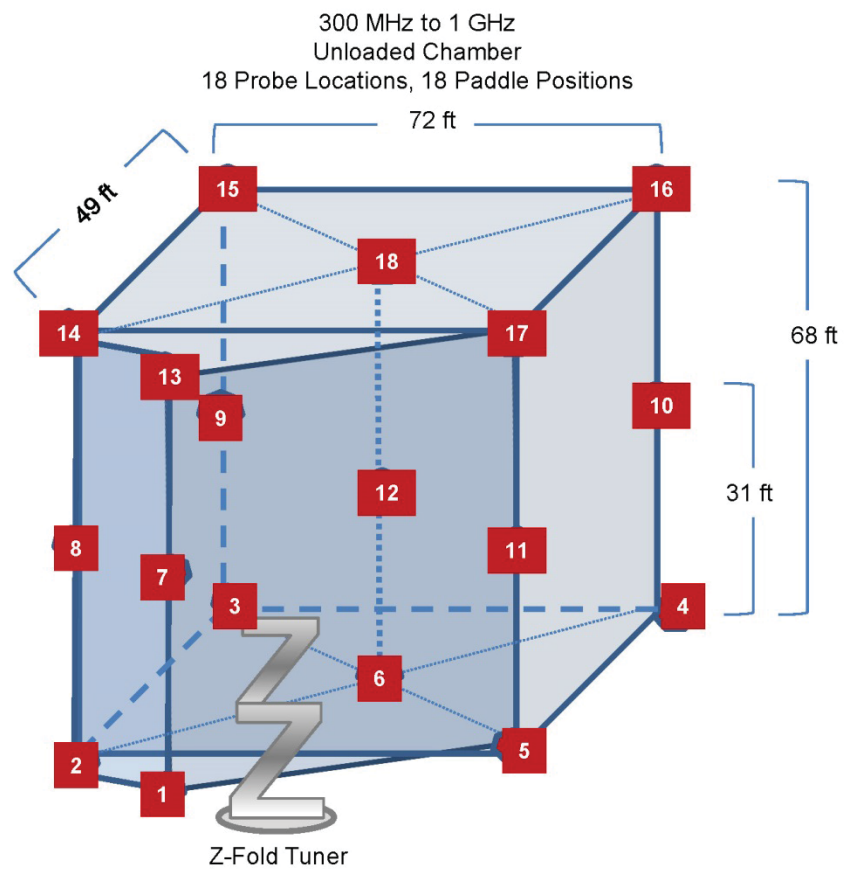


Figure B.7.—Probe Placement Configuration P6

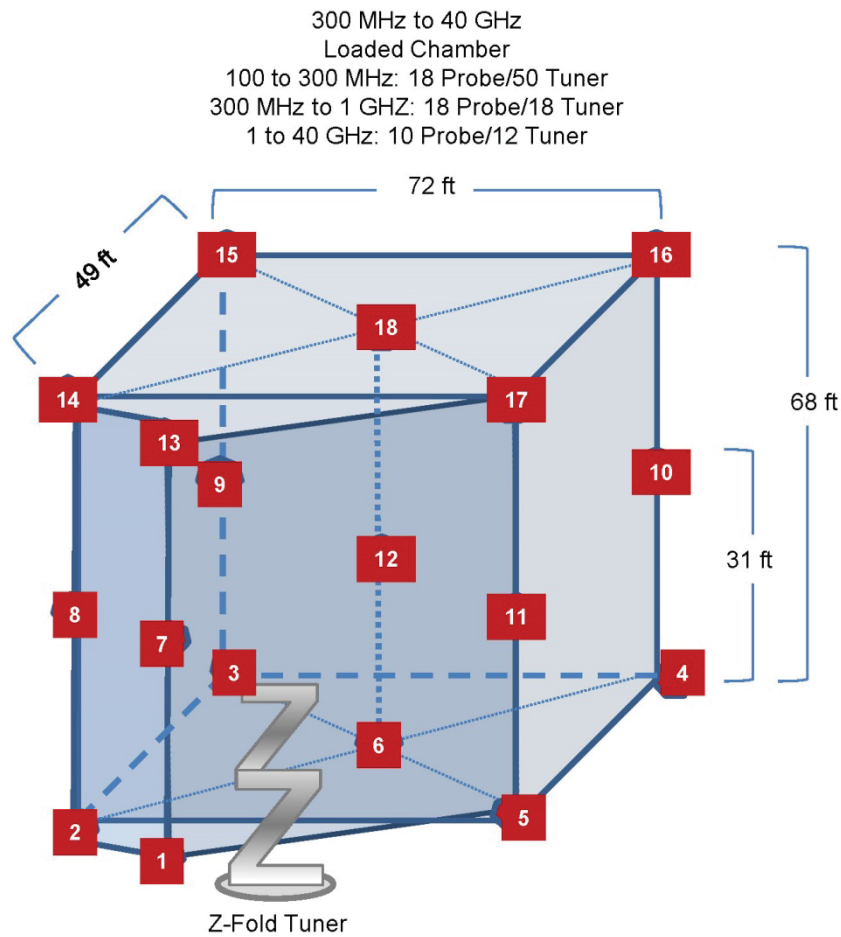


Figure B.8.—Loaded Chamber Probe Placement P6

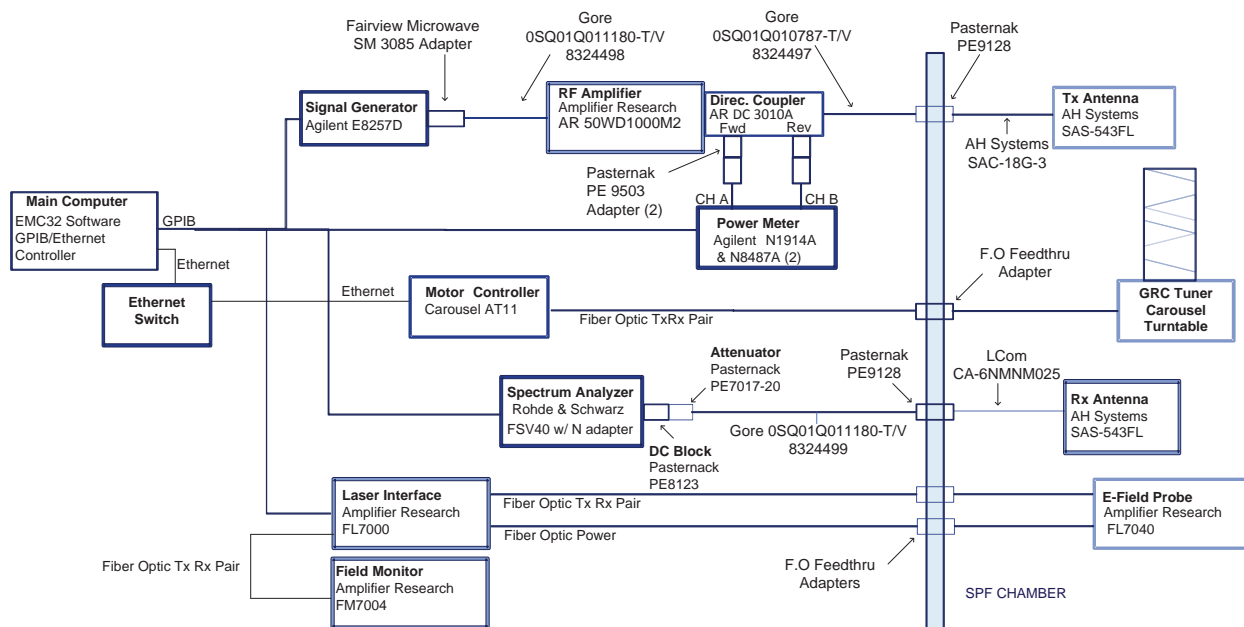
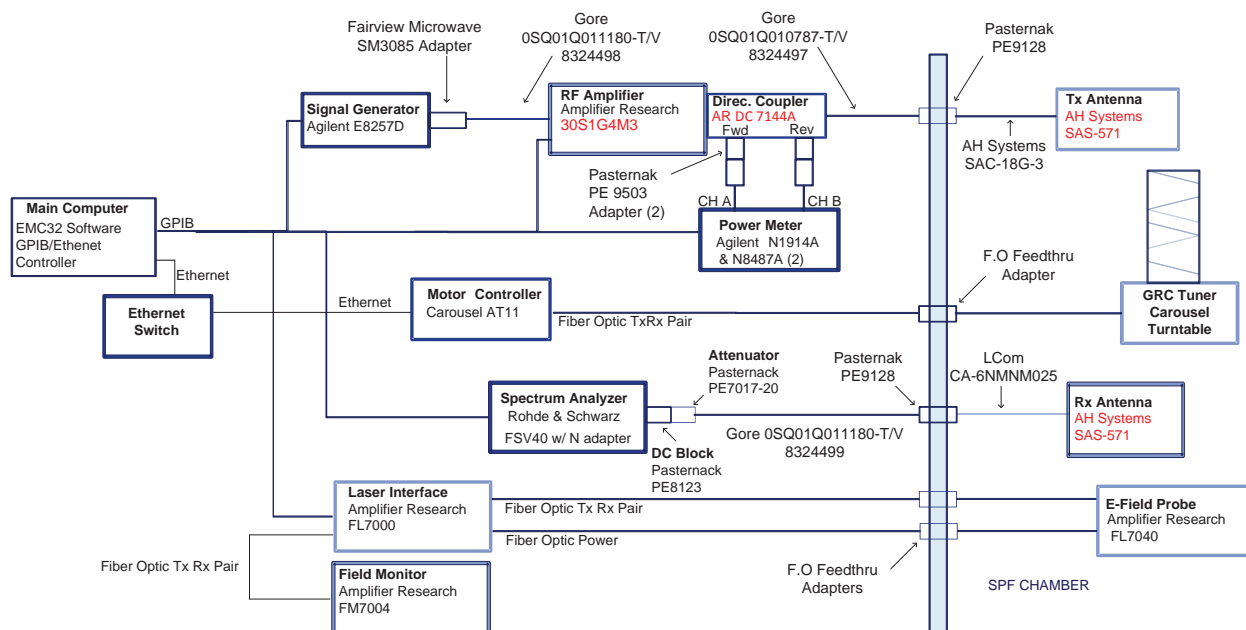
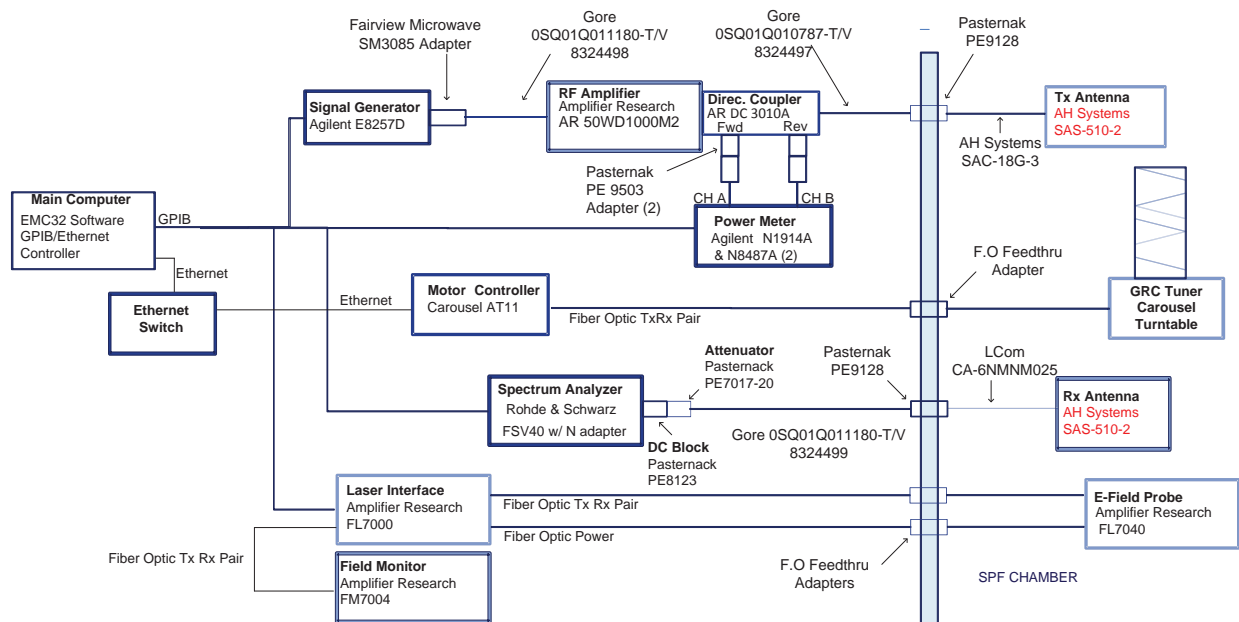


Figure B.9.—RF Equipment Setup, 100 to 300 MHz





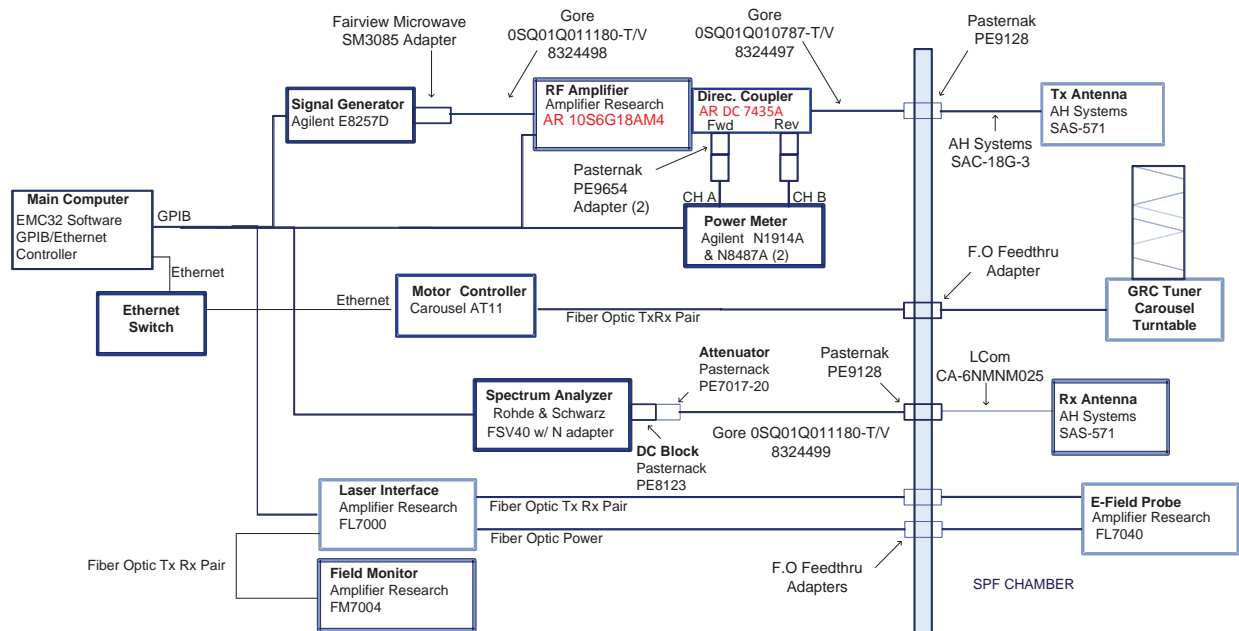


Figure B.14.—RF Equipment Setup, 8 to 18 GHz

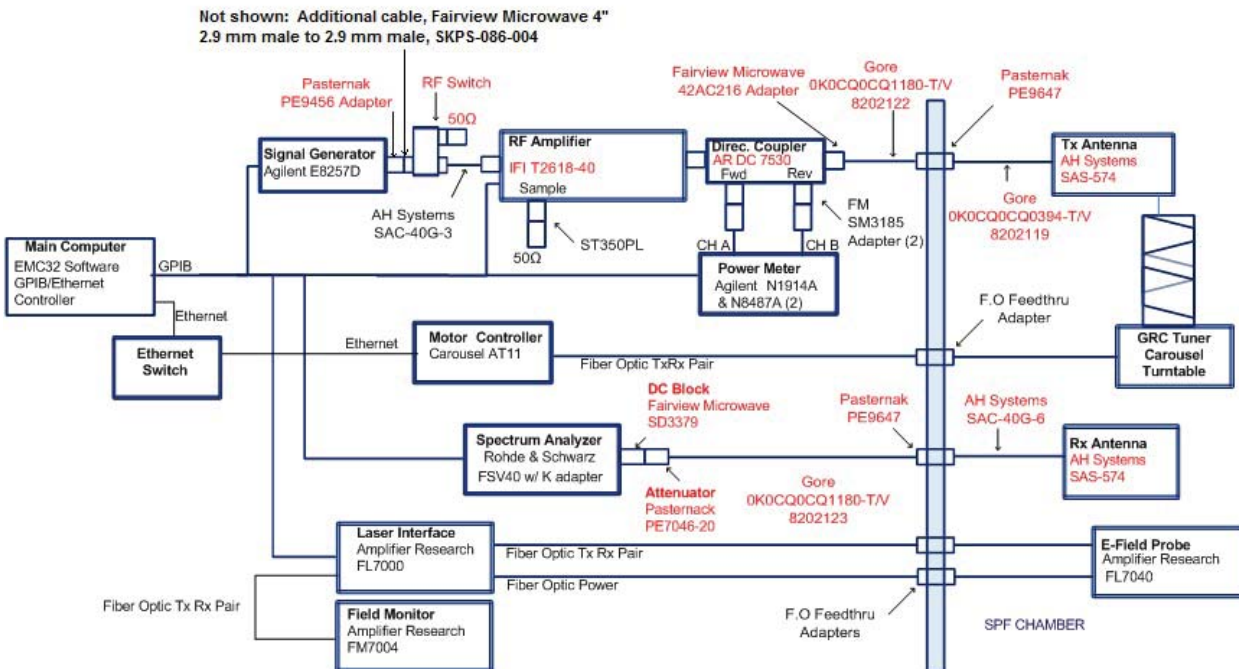


Figure B.15.—RF Equipment Setup, 18 to 26 GHz

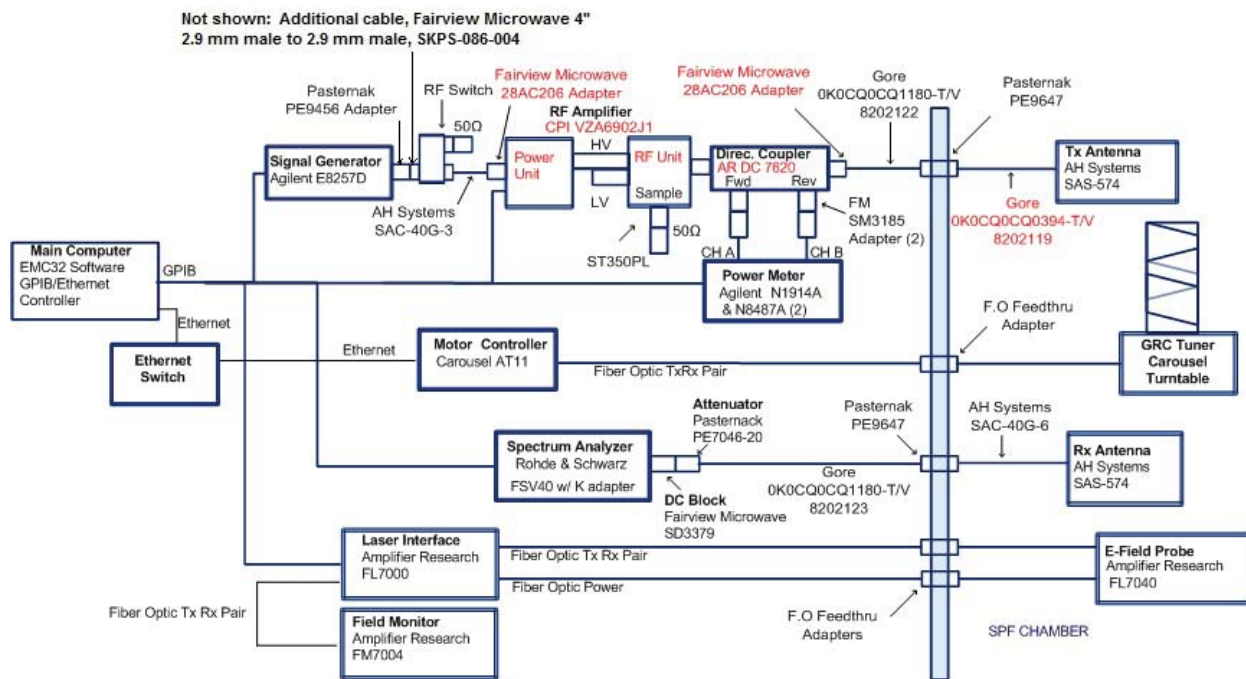


Figure B.16.—RF Equipment Setup, 26.5 to 40 GHz

Appendix C.—Relevant Equations For Chamber Loading Estimate

C.1 Chamber Parameters

$$V = \text{Volume} = 23,315 \text{ m}^3$$

$$S = \text{Surface Area} = 5,735 \text{ m}^2$$

$$\text{Material} = \text{Aluminum Alloy 3003}$$

$$\text{Aluminum 3003 Resistivity} = 3.49 \times 10^{-8} \Omega\text{-m}$$

$$\sigma = \text{Aluminum 3003 Conductivity} = 2.865 \times 10^7 \text{ Mho/m}$$

$$\mu = \text{Aluminum 3003 Permeability} = 1.256665 \times 10^{-6}$$

$$\mu_r = \text{Aluminum 3003 Relative Permeability} = 1.000022$$

$$\text{Power required} = 200 \text{ V/m} = 106 \text{ W/m}^2$$

Calculation of Theoretical Chamber Q:

$$Q = (3 * V) / (2 * S * \delta * \mu_r)$$

$$\delta = [2 / (2\pi f * \mu_o * \mu_r * \sigma)]^{1/2}$$

Calculation of Theoretical Required Transmit Power to Yield 200 V/m

$$P_t = \text{Transmit Power}$$

$$\langle S_r \rangle = \text{Scalar mean power density in the chamber} = (\lambda * Q * P_t) / (2 * \pi * V) = 106 \text{ W/m}^2$$

Theoretical Chamber Reverberation Threshold

$$Q_{\text{thr}} = [(4 * \pi) / 3]^{2/3} * [V^{1/3} / (2 * \lambda)]$$

Appendix D.—Vehicle Approximated Physical Characteristics

D.1 Geometry

The *Orion* CEV is comprised of an Outer Main Engine (OME), a Service Module (SM), a Crew Module (CM), and a Launch Abort System (LAS). The geometries were simplified for expediency, into the components shown in Figure D.1. As a result, the following parameters were calculated:

Solid Vehicle, based on the dimensions of the Outer Mold Line (OML):

$$V_{\text{veh_solid}} = 7.30 + 35.41 - 5.84 + 33.79 + 1.23 = 71.89 \text{ m}^3$$

Weight of the vehicle = 18,447 Kg (source: http://www.nasa.gov/pdf/402684main_M-2140_orion_fs_rev2.pdf)

$$\text{Density of carbon fiber composite} = 1600 \text{ Kg/m}^3$$

The worst case absorption would be if the vehicle were assumed to be 100 percent composite. In this case, the volume of composite material would equal the weight of the vehicle divided by the density of the composite

$$V_{\text{vehicle}} = 18447 / 1600 = 11.53 \text{ m}^3$$

As a sanity check for this calculation, the ratio of composite to empty space is: 11.53/71.89 to 1 – 11.53/71.89 = 16 : 84, which seems within reasonable bounds.

Surface Area of the vehicle is:

$$S_{\text{veh}} = 35 + 46.69 - 13.64 + 20.54 + 4.82 = 93.41 \text{ m}^2$$

$$CS_{\text{ave}} = \text{Ave Cross Sectional Area} \cong \text{Volume} / \text{Height} = 11.53 / (13.357+3.3+4.78+1.42) = 0.504 \text{ m}^2$$

D.2 Theoretical Electromagnetic Properties of Vehicle

$$\text{Loss Tangent} = \tan \delta = 1/Q = \sigma / (\omega \epsilon)$$

Some assumptions were made about the relationships between vehicle properties and the loading factor Q_{vehicle} .

A value for loss tangent was found to be 0.06 at 2.45 GHz. The source for this value is <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1711286>. Backing out the dependency on frequency will allow calculation of the loss tangent across the frequency spectrum of interest:

$$\sigma/\epsilon = 0.06 * 2 * \pi * 2.45 \times 10^9 = 9.236 \times 10^8.$$

To calculate the loading of the chamber by the presence of the vehicle, the following relationship between vehicle volume and cross-sectional area to the overall chamber volume was assumed.

$$Q_{\text{vehicle}} \propto V_{\text{chamber}} / (V_{\text{vehicle}} * CS_{\text{ave}})$$

$$Q_{\text{vehicle}} \cong (1/\tan \delta) [V_{\text{chamber}} / (V_{\text{vehicle}} * CS_{\text{ave}})]$$

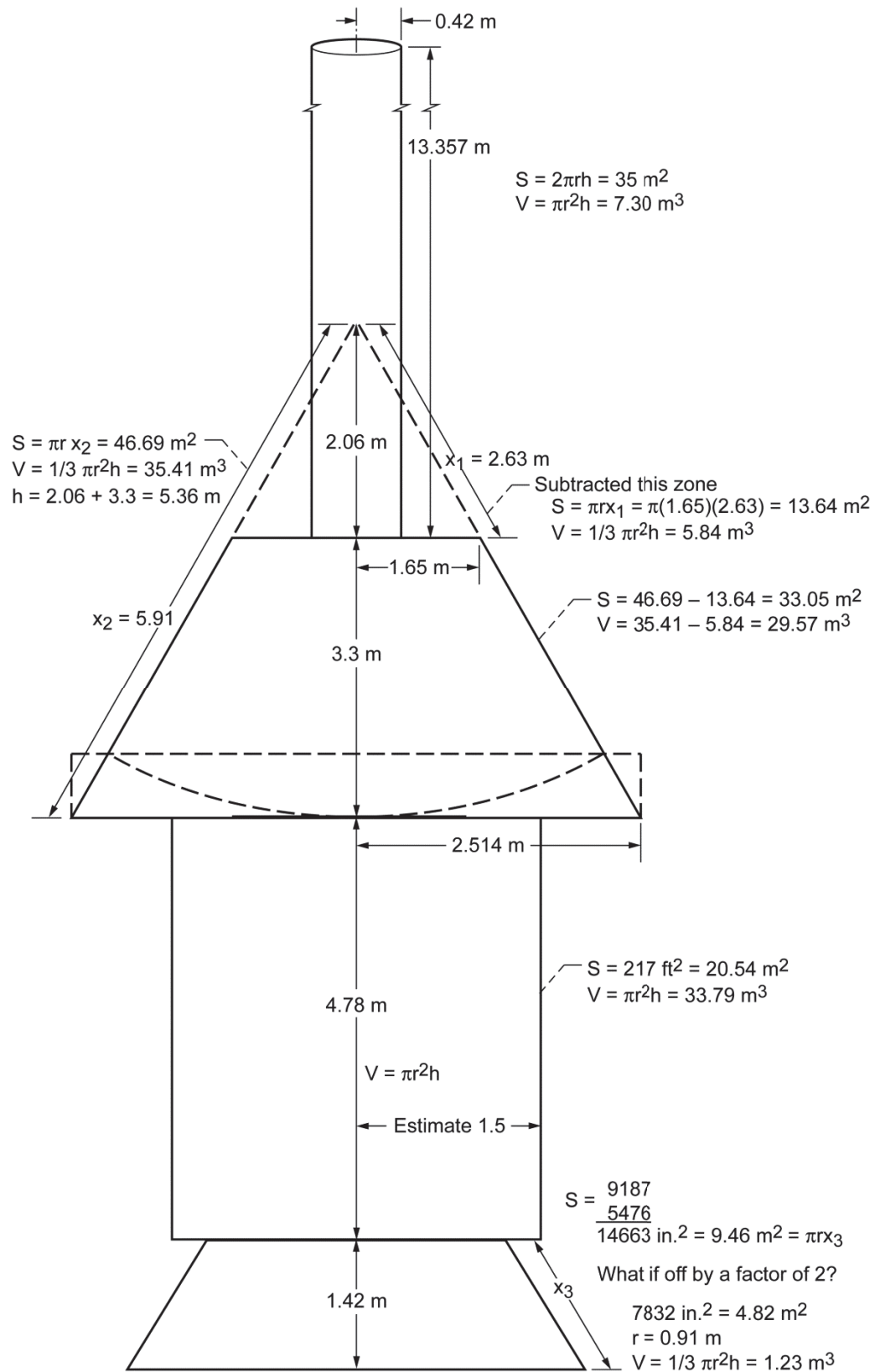


Figure D.1.—Geometries Used for the CEV Model

Appendix E.—Graphs of Calculated CEV Loading

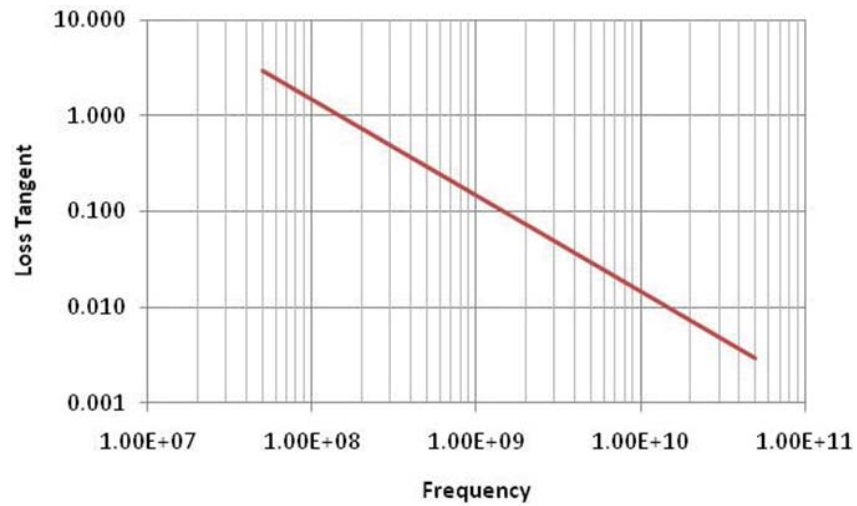


Figure E.1.—Loss Tangent of Carbon Based Resin Composite versus Frequency

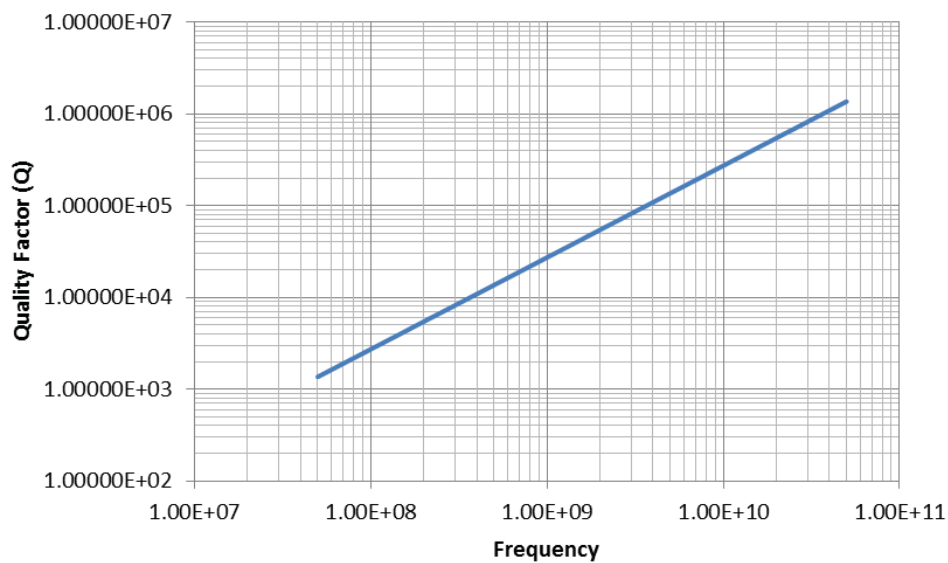


Figure E.2.—Theoretical Q of the CEV

$$Q_{\text{loaded}} = \frac{1}{1/Q_{\text{chamber}} + 1/Q_{\text{vehicle}}}$$

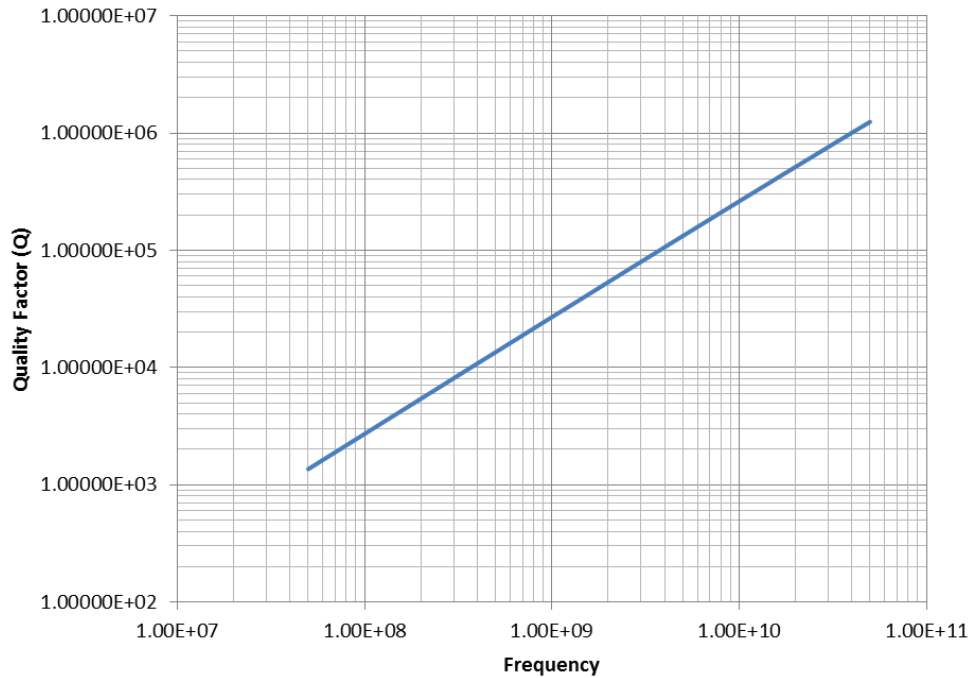


Figure E.3.—Theoretical Q of the Chamber Loaded With CEV

Theoretical Q Values of Empty Chamber, Vehicle, Loaded Chamber, and Chamber Threshold Q

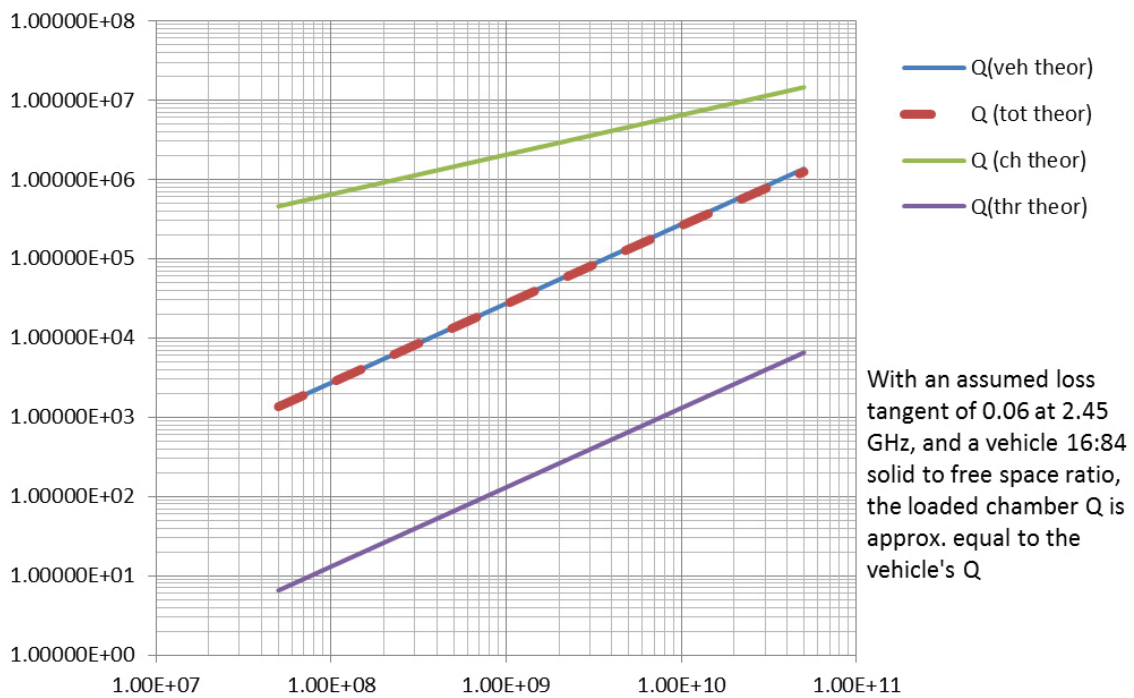


Figure E.4.—Theoretical Q of Empty Chamber, Vehicle, Loaded Chamber, and Threshold

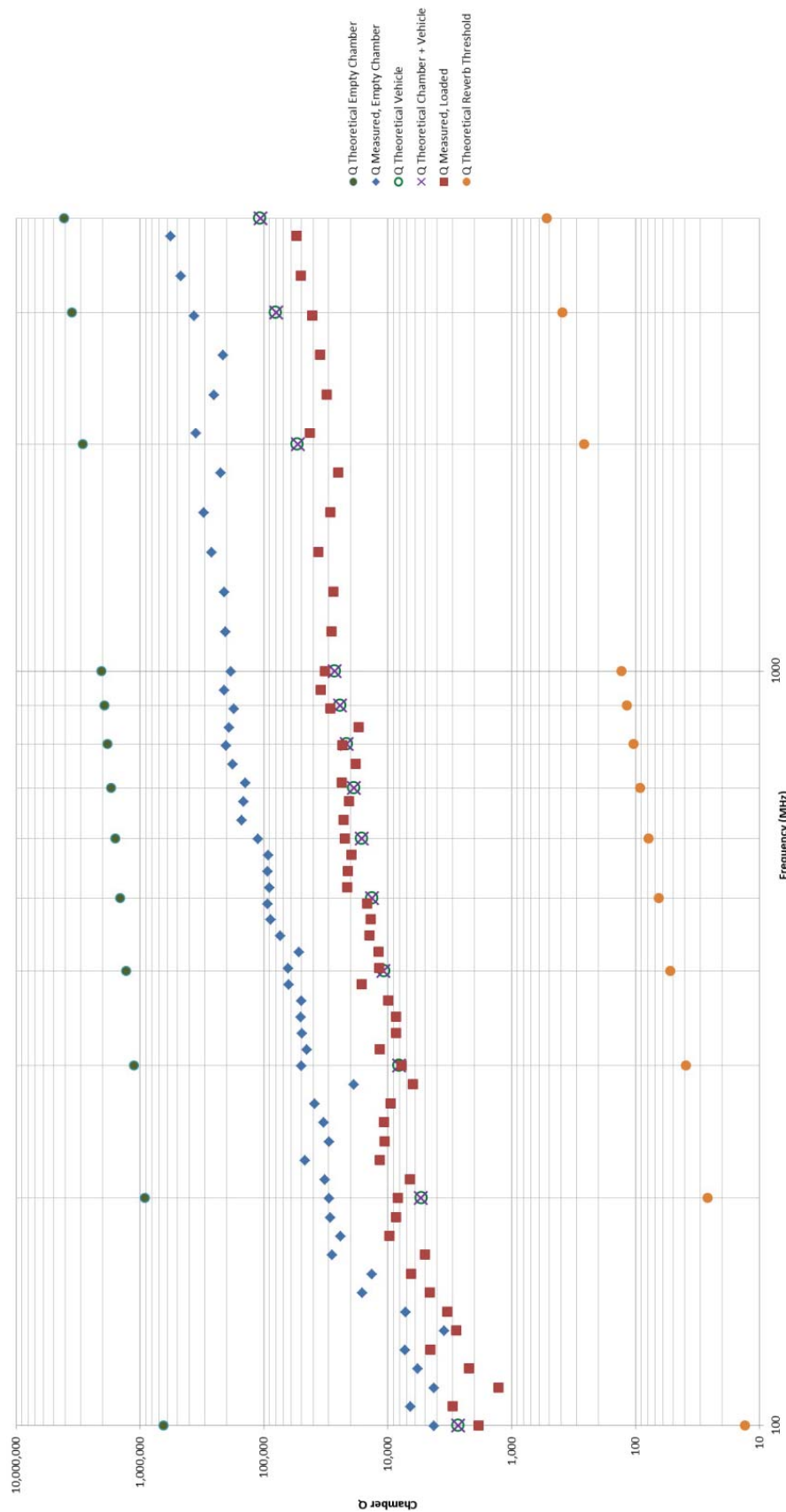


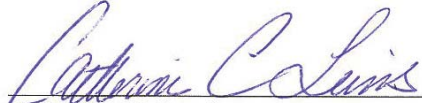
Figure E.5.—Comparison of Theoretical and Measured Q Values

Appendix F.—Document History Log

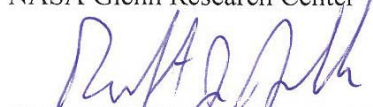
Status (Baseline/ Revision/ Canceled)	Document Revision	Effective Date	Description
Baseline	-	June 30, 2014	Late Baseline, for forward work with MPCV

**Appendix G.—Space Power Facility Reverberation
Chamber Calibration Report
Signature Page**


SUBMITTED BY:


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SET Lead Electromagnetics Engineer
NASA Glenn Research Center

6/19/14
Date

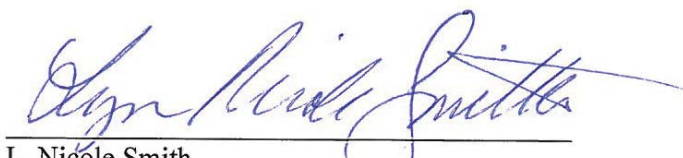

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6/25/2014
Date


Richard K. Evans
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6/25/14
Date

Appendix H.—Errata

- After the calibration procedure was performed, the Spectrum Analyzer, Rhode & Schwarz FSV40, Serial Number 100918, was sent to GRC Metrology for calibration. It was found that one or more of the measured values were outside the data sheet specifications, specifically the DC coupled RF attenuation near 40 GHz, and the Phase Noise with a 96 kHz carrier offset.
 - The RF attenuation at 10, 20, 30, and 40 dB all measured approximately -3 dB, and the limit is -2.5 dB. The impact of this out-of-range attenuation would have to be analyzed.
 - The phase noise was over the limit of 115 dBc (1 Hz) by only 0.07 dBc (1 Hz). (The measured value was 114.93 dBc (1 Hz).) It is doubtful that this out of range parameter had a measureable impact on the chamber calibration.

